JRC - SAR Satellite Small Boat Detection Campaign – Portoroz - Slovenia

Results of the Spaceborne SAR Small Boat Detection campaign carried out by the EC-JRC in Portoroz-Slovenia in May&June 2010

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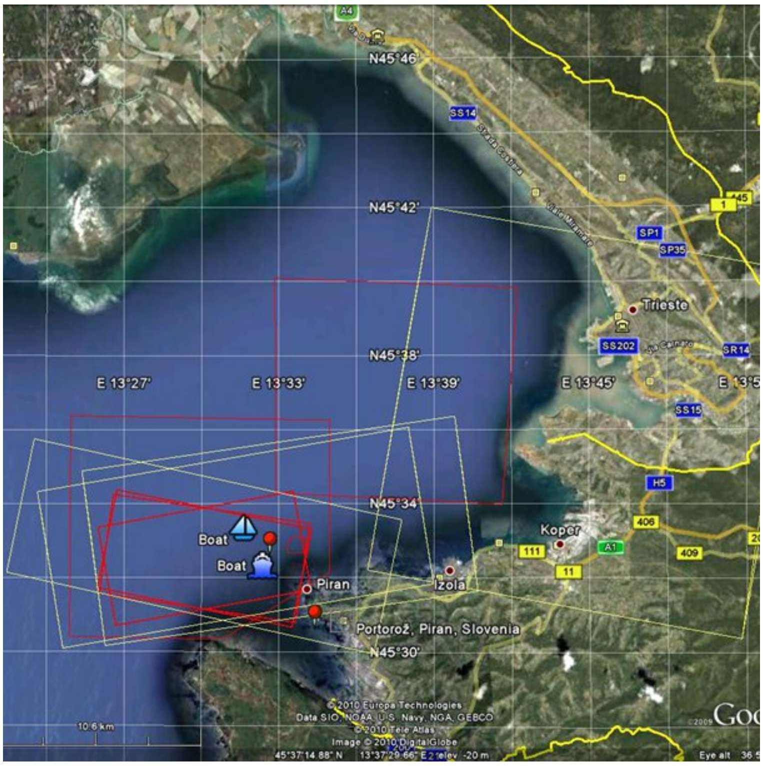

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1. – Introduction

1.1 – Scope

This report presents the key findings of the SAR Satellite Imagery Small Boat Detection Campaign, led by EC-JRC jointly with the University of Slovenia, carried out in Portoroz-Slovenia in May and June 2010.

This study addresses the feasibility of using Synthetic Aperture Radar (SAR) Satellite imagery for Small Boat Detection on open sea in Portoroz-Slovenia.

To answer this statement of work, a multinational cross-disciplinary consortium with research and operational expertise in maritime surveillance was assembled with organisations involved in:

1.- research in Maritime Surveillance using Spaceborne SAR imagery and in the processing and analysis of SAR imagery (EC-JRC).
2.- coordination and management of maritime surveillance campaigns (University of Slovenia).

1.2 – Objectives

The work was performed with the following objectives:

- To assess the feasibility of detection of Small Boats in Synthetic Aperture Radar (SAR) Satellite imagery (Radarsat2 and TerraSAR-X) on open sea.

- To characterise the SAR signature of Small Boats in SAR Satellite imagery.

- To identify the limitations of current State-of-the-Art SAR Satellite technology for maritime surveillance, in particular for Small Boat detection.

1.3 – Context

Problem Statement – The European maritime area is one of Europe's most important assets with regard to resources, security and ultimately prosperity of the Member States. A significant part of Europe's economy relies directly or indirectly on it. It is not just the shipping or fisheries industries and their related activities. It is also shipbuilding and ports, marine equipment and offshore energy, maritime and coastal tourism, aquaculture, submarine telecommunications, blue biotech and the protection of the marine environment. The European maritime area faces several risks and threats posed by unlawful activities, such as drugs trafficking, smuggling, illegal immigration, organised crime and terrorism. Piracy in international waters also constitutes a threat to Europe since it can disrupt the maritime transport chain. These risks and threats can endanger human lives, marine resources and the environment, as well as significantly disrupt the transport chain and global and local security. It is anticipated that these risks and threats will endure in the mid and long run. In order to keep Europe as a world leader in the global maritime economy, an effective integrated/interoperable, sustainable maritime surveillance system and situational awareness are needed.

A significant number of unlawful maritime activities, such as illegal immigration, drugs trafficking, smuggling, piracy and terrorism involve mainly small boats, because small boats are faster and more difficult to detect using conventional means. Hence, it is very important to find out the feasibility of using SAR Satellite images for small boat detection.

2. – Research Method

In order to find out the feasibility of using SAR Satellite imagery to detect small boats, a controlled experiment on open sea was designed, set up and executed. The controlled experiment is briefly described next.

2.1 – Controlled Experiment on Open Sea

The main objective of this controlled experiment was to find out if 7 boats of different sizes, ranging from about 6m up to 37m of known GPS position, deployed on open sea, could be detected using SAR satellite imagery, namely Radarsat2 and TerraSAR-X. Knowing the GPS positions of several boats with sizes ranging from 6m to 37m, deployed on open sea at the time of the SAR Satellite passes it should be possible to check on the SAR Satellite images if the boats were detected or not. The experiment was not blind in the sense that the EC-JRC was aware of the GPS positions of all the boats before performing a visual analysis or running the vessel detection software (SUMO).

The sequence of events of the controlled experiments was as follows:

1. - The EC-JRC checked the available SAR satellite images (Radarsat2 and TerraSAR-X) available over the region of Piran in Portoroz-Slovenia and ordered a set of selected images of different modes.

2. – On the selected dates a team of EC-JRC staff together with a team of the University of Slovenia deployed several boats carrying GPS receivers, among other sensors, on open sea at the time of the SAR satellite passes, within the SAR satellite image frame, near a oceanographic buoy.

3. – Among other data, the following parameters have been taken at the time of the satellite passes:
    a.) Sea State,
    b.) Wind Speed,
    c.) Weather conditions.

3. – Experiments Set Up

In this section we describe the experiment set up, namely the experiment site selection, the SAR Satellite Imagery planning and the partners involved and their roles.

3.1 – Experiment Site Selection - Open Sea

Bearing in mind that most unlawful maritime activities involving small boats, such as illegal immigration, drugs trafficking, smuggling and terrorist activities can be better mitigated if the small boats are detected at an earlier stage while on open sea, the selection of open sea site scenarios for the experiment was an obvious option.

The open sea trials were carried out a few miles from the coast of Portoroz, Slovenia to test the feasibility of detecting small immigrant boats at high sea during their trip from the coast of Africa towards Europe. These open sea scenarios help to prevent SAR Satellite imagery artefacts and effects due to the proximity of land coastal targets. The open sea sites selected were all located a few nautical miles away from the coast.

3.1.1 – Open Sea Sites in Slovenia

The open sea sites selected in Slovenia were near Piran a few nautical miles away from the coast, near an oceanographic buoy, and a few nautical miles from Zola, as illustrated in fig.1.

Figure 1 – Open sea experiment sites near Piran – Slovenia.

3.3 – SAR Satellite Imagery Planning

Figure 2 illustrates the SAR Satellite imagery planning. The footprints of the SAR Satellite images selected are shown in the google earth image of the region of Portoroz.

The Synthetic Aperture Radar (SAR) satellite imagery used in this experiment comprised Radarsat2 (Spotlight and Ultrafine) and TerraSAR-X (Spotlight and Stripmap). Figures 4 and 5 illustrate the Radarsat2 image modes and the TerraSAR-X image modes, respectively. Table-1 illustrates the SAR satellite Images and Modes used in the different days of the experiment. The SAR satellite images were acquired over the Gulf of Cagliari, Porto Pino, Porto Canale beach in Sardinia-Italy and over Palomares Canyon in Spain.

Figure 2 – Footprints of the SAR Satellite images acquired over Piran, Portoroz-Slovenia.

The Radarsat2 and TerraSAR-X image modes used in the present experiment will be briefly reviewed in the next paragraphs.

Radarsat2 - Spotlight Mode – The Spotlight Beams are intended for applications which require the best spatial resolution available from the RADARSAT-2 SAR system [Rng x Az] (m), [1.6 x 0.8] (m). In this mode the radar operates with the highest sampling rate, and so the ground swath coverage is limited to keep data rate within the recorder limits. Unlike the other modes, Spotlight images are also of fixed size in the along track direction.

The set of Spotlight Beams cover any area within the incidence angle range from 20 to 49 degrees. Each beam within the set images a swath width of at least 18 km. Spotlight images can only be generated in a single polarization, which can be either a linear co-polarization (HH or VV) or a linear cross-polarization (HV or VH).

Figure 3 illustrates all available Radarsat2 image beam modes. The beam modes more adequate for small boat detection are the Spotlight and the Ultrafine due to their high resolution.

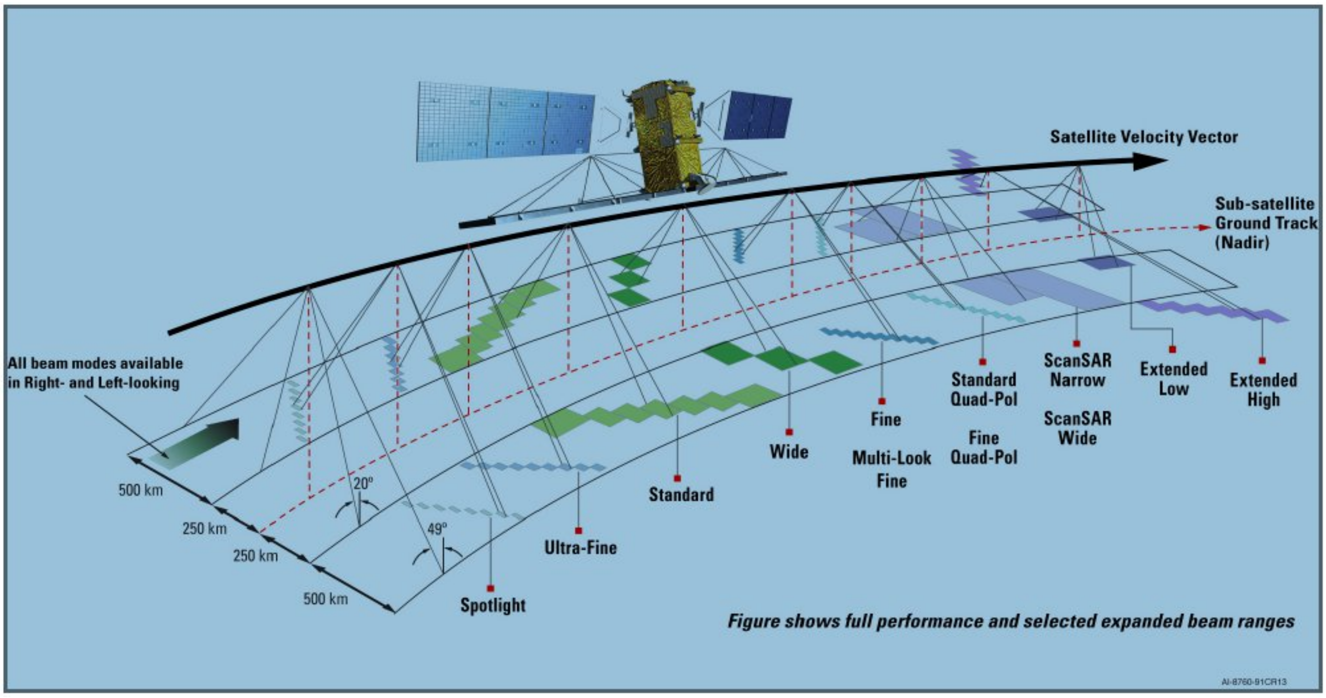


Figure 3 – Radarsart2 image modes. The Ultrafine and the Spotlight modes have been identified as the most suitable modes for this particular experiment.

Radarsat2 - Single Beam Mode – Single beam mode is a stripmap SAR mode. In Single Beam operation, the beam elevation and profile are maintained constant throughout the data collection period. The following Single Beam modes are available: Standard, Wide, Fine, Multi-Look Fine, Ultra-Fine, Extended High (High Incidence), Extended Low (Low Incidence), Standard Quad Polarization and Fine Quad Polarization. We selected Ultra-Fine because it is the best compromise between swath coverage and resolution.

Radarsat2 - Ultra-Fine – The Ultra-Fine Resolution Beams are intended for applications which require very high spatial resolution. In this mode the radar operates with the highest sampling rate, and so the ground swath coverage is limited to keep data rate within the incidence angle from 20 to 49 degrees. Each beam within the set images a swath width of at least 20 km. Ultra-Fine Resolution images can only be generated in a single cross-polarization , which can be either a linear co-polarization (HH or VV) or a linear cross-polarization (HV or VH).

The **standard TerraSAR-X operational mode** is the single receive antenna mode from which the following imaging modes can be retrieved: High Resolution Spotlight and Spotlight, StripMap, and ScanSAR. The single receive antenna mode uses a chirp
bandwidth of up to 300 MHz.

Figure 4 illustrates all available TerraSAR-X image beam modes. The beam modes more adequate for small boat detection are the Spotlight and the Stripmap due to their high resolution.

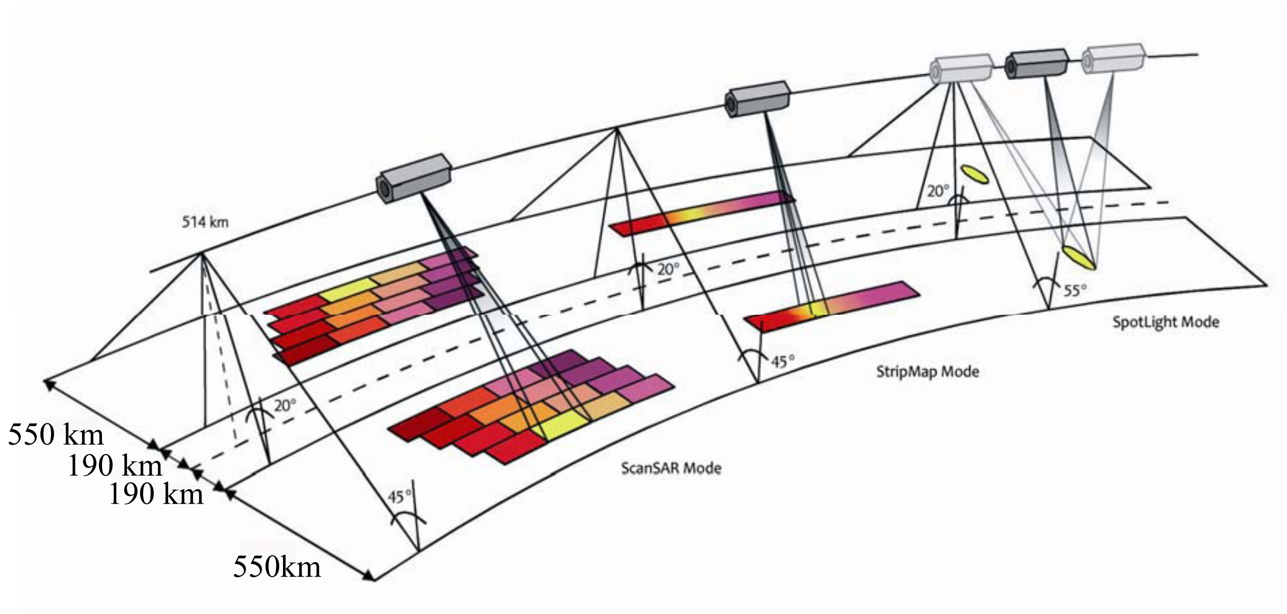


Figure 4 – Radarsart2 image modes. The Ultrafine and the Spotlight modes have been identified as the most suitable modes for this particular experiment.

The **SpotLight (SL)** imaging modes use phased array beam steering in azimuth direction to increase the illumination time, i.e. the size of the synthetic aperture. This leads to a restriction in the image / scene size. Thus, the scene size is technically restricted to a defined size: 10 km x 10 km for the SpotLight mode and 10 km x 5 km (width x length) in the HighResolution SpotLight (HS) mode.

This sophisticated imaging mode makes it possible to acquire data with up to 1 m resolution in the HighResolution SpotLight mode (acquired with a bandwidth of 300 MHz) and 2 m in the standard SpotLight mode.

StripMap (SM) is the basic SAR imaging mode as known e.g. from ERS-1 and other radar satellites. The ground swath is illuminated with continuous sequence of pulses while the antenna beam is fixed in elevation and azimuth. This results in an image strip with a continuous image quality (in flight direction). StripMap dual polarisation data have a slightly lower spatial resolution and smaller swath than the single polarisation data.

In StripMap mode, a spatial resolution of up to 3 m can be achieved. The standard scene size is 30 km x 50 m (width x length) in order to obtain manageable image files; however, acquisition length is extendable up to 1,650 km.

The planning of all the SAR satellite images acquired during this campaign is illustrated in the sequence of figures given next (Fig.5 to Fig.17). For small boat detection in restricted areas, the Spotlight mode seems to be the best. For wide maritime surveillance larger swath widths seem to be more adequate.

Table 1 – SAR satellite imagery acquired over Piran, Portoroz-Slovenia.

Date/Time	Area	Satellite / Mode	Polarization	Pass
17.May.2010 (AM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	Single HH	Descending
17.May.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	Single HH	Ascending
18.May.2010 (AM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	Single HH	Descending
31.May.2010 (PM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	Single HH	Ascending
31.May.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	Single HH	Ascending
01.Jun.2010 (AM)	Portoroz- Slovenia	Radarsat-2 / Ultrafine	Single HH	Descending
04.Jun.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	Single HH	Ascending

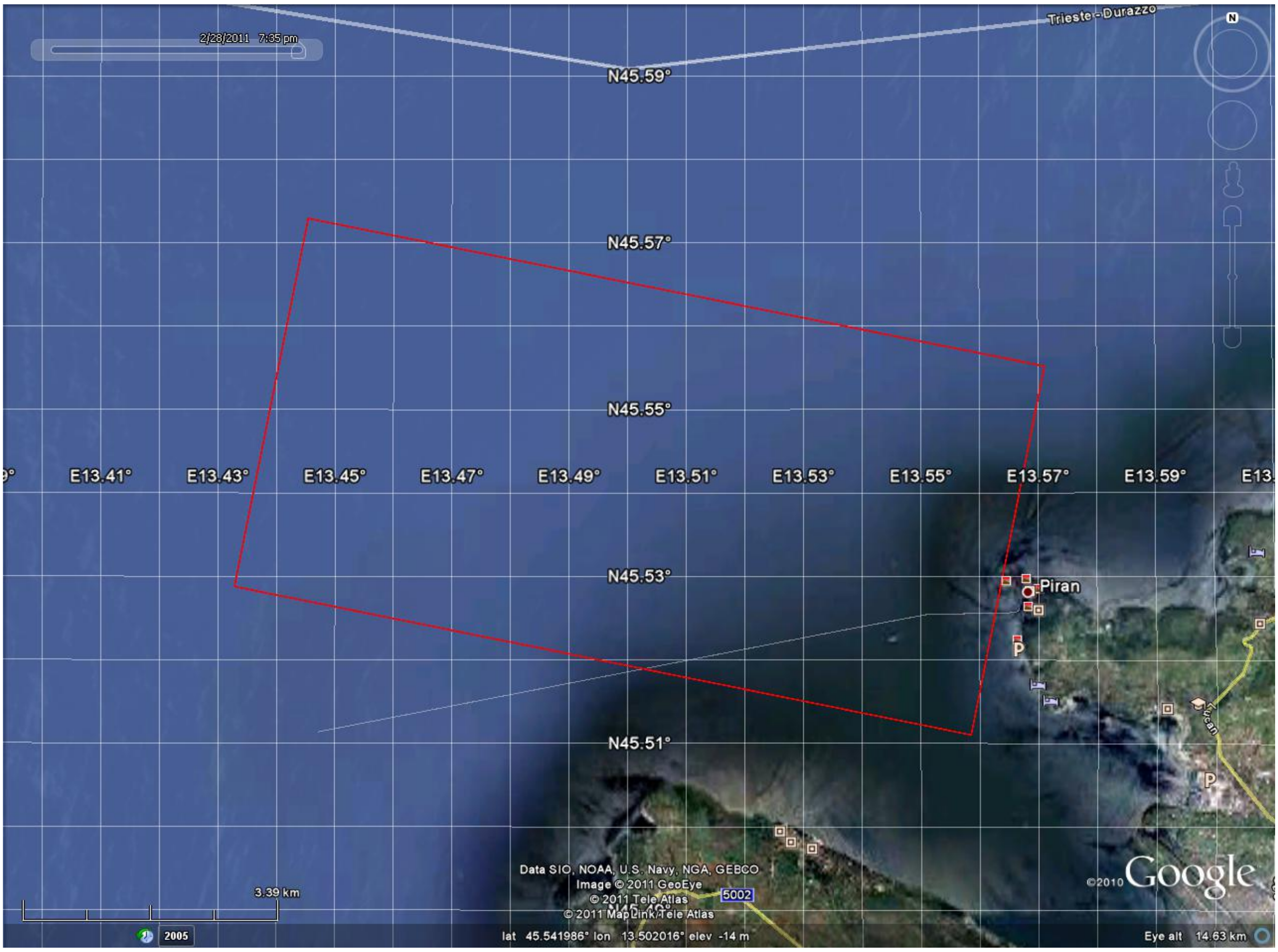


Figure 5 – TerraSAR-X Spotlight imagery planning for 17 May.2010, Piran, Portoroz-Slovenia.

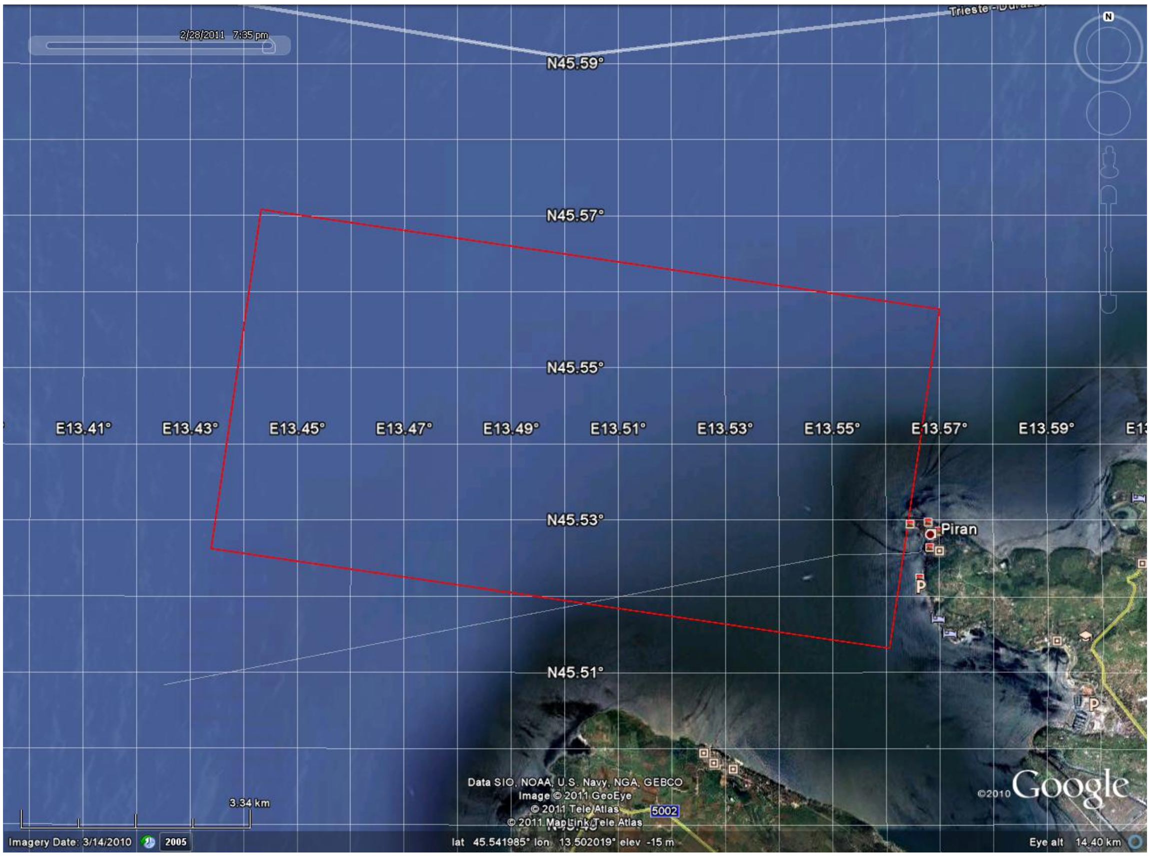


Figure 6 – TerraSAR-X Spotlight imagery planning for 18 May.2010, Piran, Portoroz-Slovenia.

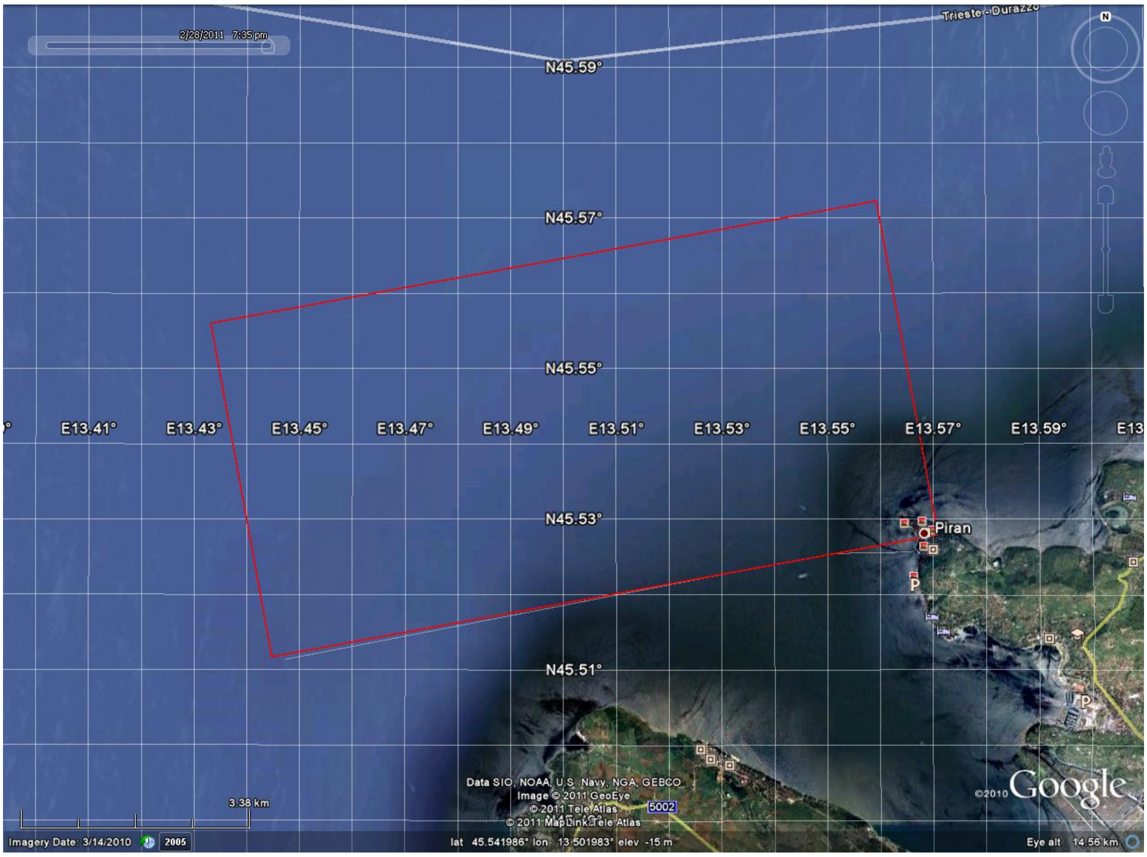


Figure 7 – TerraSAR-X Spotlight imagery planning for 31 May.2010, Piran, Portoroz-Slovenia.

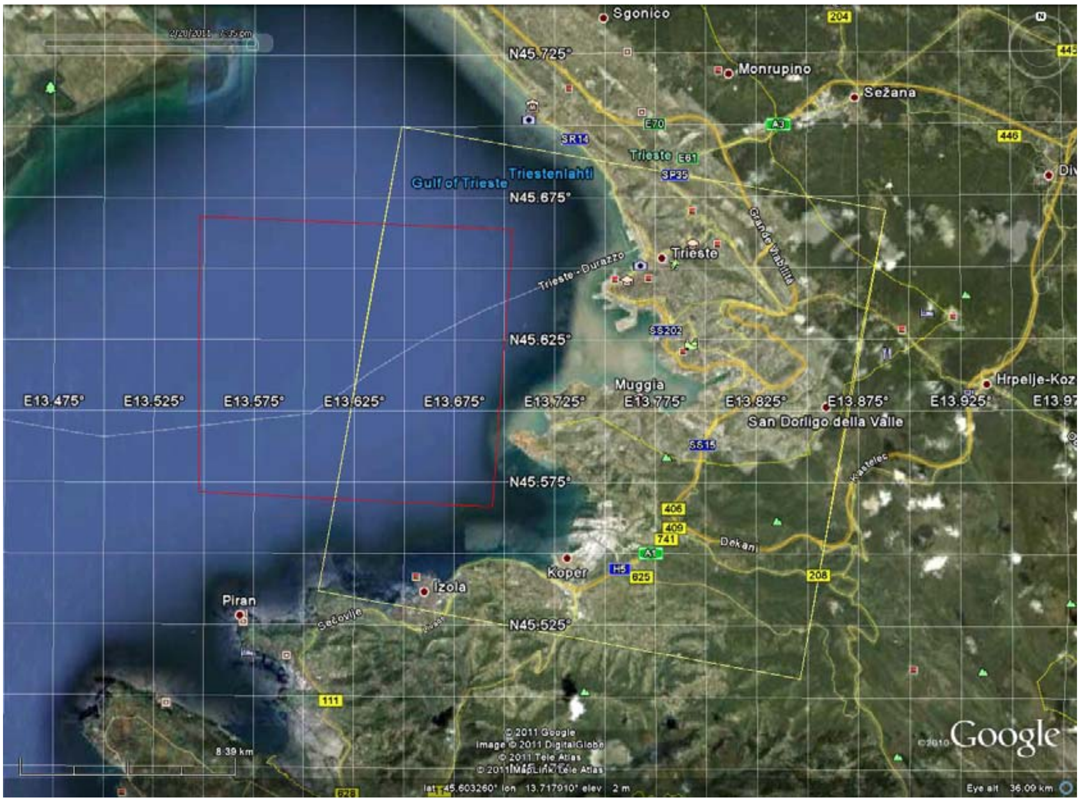


Figure 8 – Radarsat2, Mode Ultrafine, single polarization HH, Descending pass, 01Jun.2010, Izola-Slovenia. In red the Trieste region and in yellow the Radarsat2 Ultrafine image footprint.

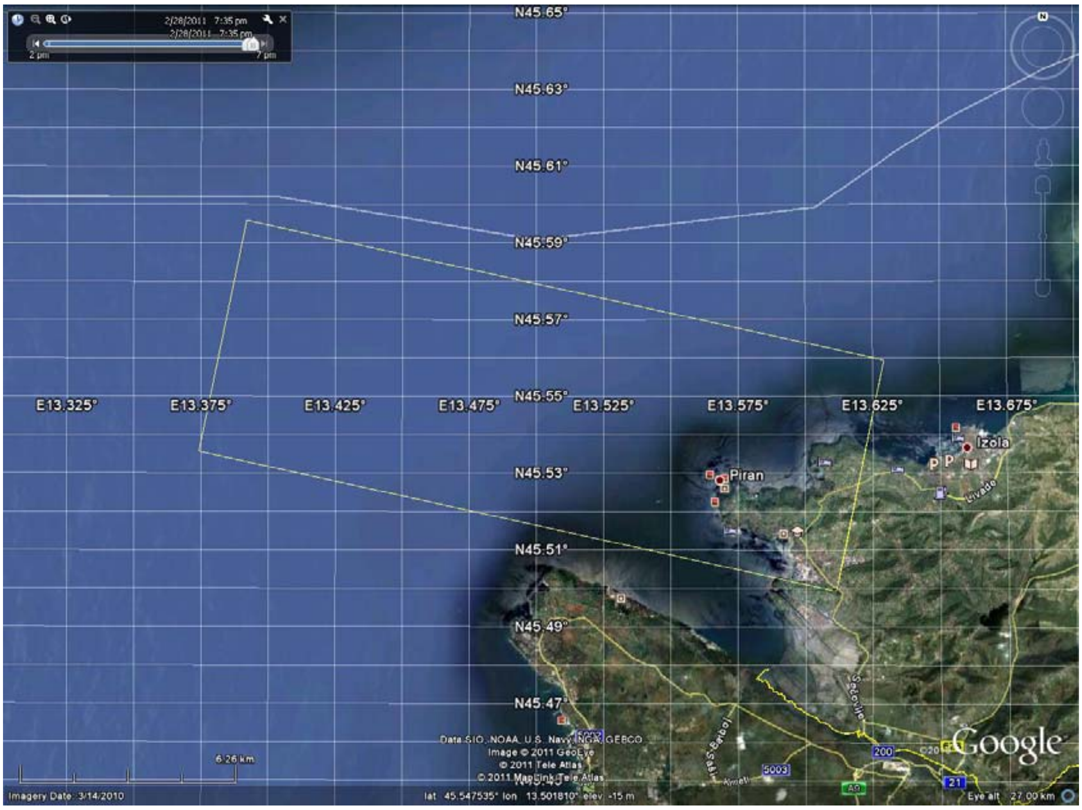


Figure 9 – Radarsat2, Mode Spotlight, single polarization HH, Ascending pass, 04Jun.2010, Piran-Slovenia. In yellow the Radarsat2 Spotlight image footprint.

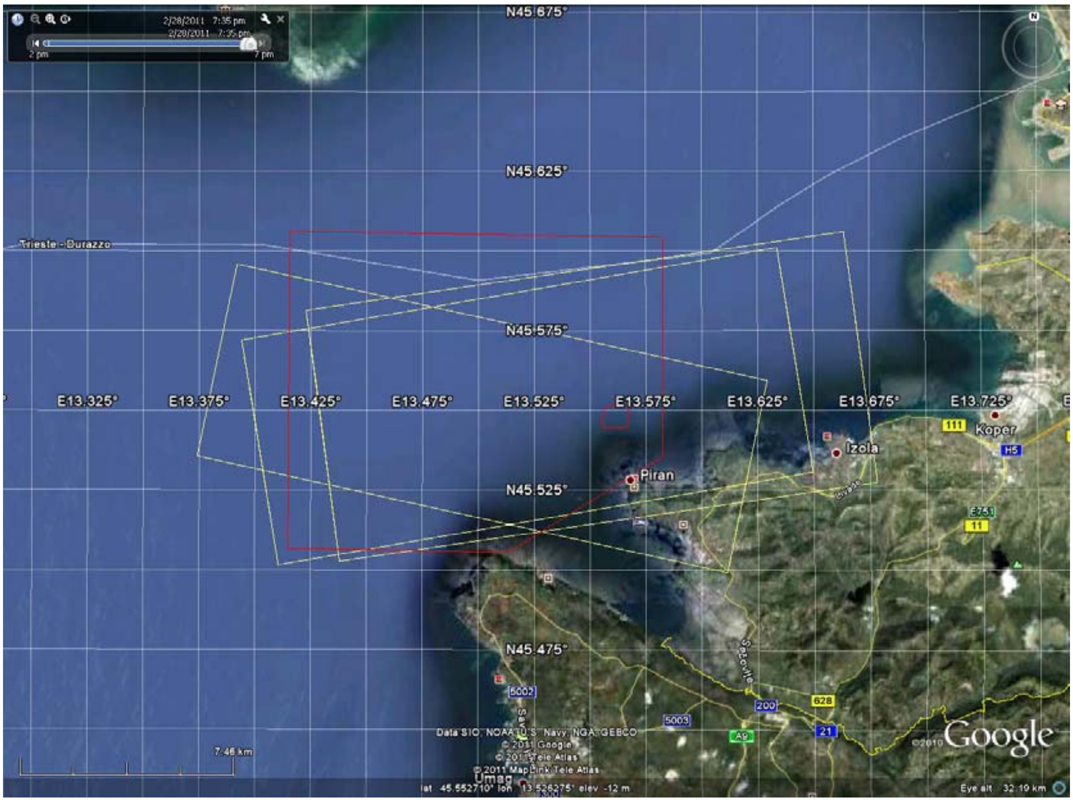


Figure 10 – Radarsat2, Mode Spotlight, single polarization HH, Ascending passes, 17&31May&04June2010, Piran-Slovenia. In yellow the Radarsat2 Spotlight images footprints. In red the large polygon illustrates the region used to perform the planning. In red the small polygon illustrates the region where the oceanographic buoy "Vida" is moored a few nautical miles North of Piran.

3.4 – Partners Involved and their Roles

The partners involved in this experiment include:

3.4.1 - European Commission (EC) – Joint Research Centre (JRC)

– The main role of the EC-JRC was to design and set up the research study involved in the experiment. This comprised:

a.) the definition of the objectives,
b.) the research methods used,
c.) the ground truth data collection,
d.) the analysis of the data and
e.) the conclusions of the experiment.

3.4.2 – The University of Ljubljana

– The main role of the University of Ljubljana comprised:

a.) the deployment of the boats used as targets.
b.) the contacts with the Slovenian authorities.

c.) the collection of ground truth data.

4. – Experiment Execution

4.1 – Open Sea - Modus Operandi

The modus operandi of the trial on open sea was as follows:

1.- JRC supplied the University of Ljubljana with the footprints (frames) of the SAR satellite images to be acquired, as well as the times of the SAR satellite passes.

2.- The University of Ljubjana deployed five boats with sizes ranging from 6m up to 37m a few nautical miles from Piran near an oceanographic buoy with the necessary equipment to collect ground truth data at the time of the SAR satellite passes.

3.- The EC-JRC staff and the staff from the University Ljubjana collected ground truth data at the time of the SAR satellite passes.

4.- The ground truth data collected comprised:

a.) the sea state
b.) the wind speed
d.) the weather conditions
e.) Photos and movies of the boats involved in the experiment.

5.- Relevant data (GPS positions of the boats, sea/wind/weather conditions) were exchanged among concerned partners.

4.2 – Ground Truth Data Collection

The ground truth data collected during the experiment comprised the GPS position of all boats deployed, photos and videos with the relative position, the sea state, the wind speed and several wave and current parameters collected by the Oceanographic buoy moored near Piran.

4.3 – Means Deployed by the Partners

The means deployed by the University of Ljubjana comprised 7 boats with sizes ranging from 6 up to 37m. Figures 11 to 18 illustrate the different boats deployed during the experiment. The boats have different sizes, shapes and are made of different materials. Valentina, in figure 11, is rubber made with smooth surfaces and about 6 meter long. The expected SAR signature is likely weak due to the characteristics described. The boat in figure 12, named SAR, is also rubber made and has a similar shape, but is slightly longer (7.6 meter). It should originate a similar SAR signature. The sailboat, in figure 13, is wooden made with some metal fittings and a mast. The shape is not as smooth as the shape of the two rubber boats. Depending on the sea state and on the wind speed, a slightly stronger SAR signature is expected due to the mast and to the less smooth structure.

Figure 11 – A rubber boat named "Valentina" with an approximate size of 5.8m. This was the smallest boat deployed during the experiment.

The boat in Figure 14, called Slovenia, has a different shape and structure with metal fittings. The SAR signature should be slightly stronger than the previously described boats. The yachts in figures 15 and 16 (Dominator II and Dominator I, respectively) are significantly bigger and have metal fittings. Their SAR signatures should be significantly stronger. The buoy in figure 17 has a diameter of 2.5 meter and a height of about 5 meter. Since it has metal fittings and the structure above the water moves like a mast, it should be detected despite of its small size. Finally, the Burja, in figure 18, was the bigger ship with about 37 meter and metallic structure. It should give relatively strong SAR signatures compared to the other boats described above.

Figure 12 – Search and Rescue (SAR) rubber boat with an approximate size of 7.6m.

Figure 13 – A Sailboat with an approximate size of 10m.

Figure 14 – This boat named “Slovenia” belongs to the University of Ljubjana and as an approximate size of 12m.

Figure 15 – Dominator II is a 20.7m long yacht deployed during the experiment.

Figure 16 – Dominator II is a 23.7m long yacht deployed during the experiment.

Figure 17 – Oceanographic Buoy moored a few nautical miles North of Piran near which the boats where deployed. This oceanographic buoy has an approximate diameter of 2.5m.

Figure 18 – The largest boat deployed during the experiment was the “Burja” a 37m long boat.

5. – Preliminary Data Analysis

5.1 – SAR Satellite Imagery Processing

The high resolution SAR satellite images were analysed visually, since the resolution is good enough to allow visual analysis. The lower resolution SAR satellite images (eg. Radarsat2-Ultra-Fine) were also analysed visually because the GPS positions of all targets deployed were known.

5.2 – Ground Truth Data

This section briefly describes the Ground Truth data, namely the GPS positions of the boats deployed as targets during the experiment, photos of the boats, as well as other relevant ground truth data collected, including the weather conditions.

5.2.1 – GPS coordinates of the boats deployed

Tables 2 to 8 give the GPS coordinates of each boat deployed during the experiment.

Table 2 – Ground Truth data collected during the experiment on 17 may 2010.

Date: 17.May.2010 **Time:** 5:27AM UTC**-** (7:27AM LT) **/ Pass:** Descending		**Satellite/Mode:** TerraSAR-X / Spotlight **Polarisation** HH	
Boats	**Type / Size**	**Latitude**	**Longitude**
Valentina		N 45° 32.964’ N 45°32'57.84"	E 13° 32.791’ E 13°32'47.46"
SAR		N 45° 32.970' N 45°32'58.20"	E 13° 32.857' E 13°32'51.42"

Sailboat		N 45° 32.955' N 45°32'57.30"	E 13° 32.844' E 13°32'50.64"
Slovenia		N 45° 32.965' N 45°32'57.90"	E 13° 32.895' E 13°32'53.70"
Dominator-II		N 45° 32.8880' N 45° 32' 53.28"	E 13° 34.1175' E 13° 34' 7.08"
Burja		N 45° 32.9233' N 45°32'55.40"	E 13° 32.8111' E 13°32'48.66"
Buoy		N 45° 32' 55.68"	E 13° 33' 1.89"

Table 3 – Ground Truth data collected during the experiment on 17 may 2010.

Date: 17.May.2010 **Time:** 17:10 UTC-(15:27AM LT) / **Pass:** Ascending		**Satellite/Mode:** Radarsat2 / Spotlight **Polarisation** HH	
Boats	**Type / Size**	**Latitude**	**Longitude**
Valentina		N 45°33'8.58"	E 13°32'50.83"
Sailboat		N 45° 33' 05"	E 13° 32' 50"

Slovenia		N 45° 33' 06"	E 13° 32' 46"
Dominator-I		N 45° 33.2134' N 45°33'12.78"	E 13° 33.0938' E 13°32'59.70"
Burja		N 45°33.1122' N 45°33'7.14"	E 13°32.9950' E 13°33'0.42"
Buoy		N 45° 32' 55,68"	E 13° 33' 01,89"

Table 4 – Ground Truth data collected during the experiment on 18 May 2010.

Date: 18.May.2010 **Time:** 5:10AM UTC-(7:10AM LT) / **Pass:** Descending		**Satellite/Mode:** TerraSAR-X / Spotlight **Polarisation** HH	
Boats	**Type / Size**	**Latitude**	**Longitude**
Valentina		N 45 32.8344	E 13 32.7245
SAR			
Sailboat		N 45°32'59"	E 13°32'57"

Slovenia		N 45°32'55"	E 13°32'55"
Dominator		N 45 33.0175	E 1332.7019
Burja		N 45 33.0062	E 13 32.5912
Buoy		N 45° 32' 55,68"	E 13° 33' 01,89"

Table 5 – Ground Truth data collected during the experiment on 31 May 2010.

Date: 31.May.2010 **Time:** 16:50 UTC-(18:50AM LT) / **Pass:** Ascending		**Satellite/Mode:**TerraSAR-X / Spotlight **Polarisation** HH	
Boats	**Type / Size**	**Latitude**	**Longitude**
Valentina		N 45° 33.041' N 45°33'2.46"	E13° 32.160' E 13°32'9.60"
Slovenia		N 45° 33.2459' N 45°33'14.75"	E 13° 31.9634' E 13°31'57.78"

Dominator.68		N 45° 32.9253' N 45°32'55.50"	E 13° 32.6586' E 13°32'39.52"
Dominator.92b		N 45° 32.8716' N 45°32'52.32"	E 13° 32.6305' E 13°32'37.83"
Sailboat		N 45°33'01" N	E 13°32'32"
Buoy		N 45° 32' 55,68"	E 13° 33' 01,89"

Table 6 – Ground Truth data collected during the experiment on 31 May 2010.

Date: 31.May.2010 **Time:** 17:02 UTC-(19:02AM LT) / **Pass:** Ascending		**Satellite/Mode:** Radarsat2 / Spotlight **Polarisation** HH	
Boats	**Type / Size**	**Latitude**	**Longitude**
Valentina		N 45° 33.133' N 45°33'08"	E 13° 31.950' E 13°31'57"
Slovenia		N 45° 33.2784' N 45°33'16.68"	E 13° 31.7514' E 13°31'45.08"

Dominator.92		N 45° 32.8782' N 45°32'52.68"	E 13° 32.4802' E 13°32'28.81"
Dominator.68		N 45° 32.9447' N 45°32'56.70"	E 13° 32.4684' E 13°32'28.10"
Sailboat		N 45° 33.050' N 45° 33' 03"	E13° 32.550' E 13°32'33"
Buoy		N 45° 32' 55.68"	E 13° 33' 01.89"

Table 7 – Ground Truth data collected during the experiment on 01 June 2010.

Date: 01.June.2010 **Time:** 05:13 UTC-(07:13AM LT) / **Pass:** Descending		**Satellite/Mode:** Radarsat2 / Spotlight **Polarisation** HH	
Boats	**Type / Size**	**Latitude**	**Longitude**
Valentina		N 45° 33.184' N 45°33'11.04"	E 13° 38.408' E 13°38'24.48"
Dominator.92		N 45° 33.5598' N 45°33'33.60"	E 13° 39.2552' E 13°39'15.31"

Dominator.68		N 45° 33.4793' N 45°33'28.74"	E 13° 39.2802' E 13°39'16.81"

Table 8 – Ground Truth data collected during the experiment on 04 June 2010.

Date: 04.June.2010 **Time:** 05:25 UTC-(07:13AM LT) / **Pass:** Ascending		**Satellite/Mode:** Radarsat2 / Spotlight **Polarisation** HH	
Boats	**Type / Size**	**Latitude**	**Longitude**
Valentina		N 45° 32.850’	E 13° 32.146’
Slovenia		N 45° 32.8865’	E 13° 32.1648’
Dominator.92a		N 45° 32.7396’	E 13° 32.8172’
Burja		N 45° 32.9039’	E 13° 32.3916’
Buoy		N 45° 32' 55.68"	E 13° 33' 01.89"

5.3 – Weather Conditions

This section gives the Weather conditions supplied by the Marine Biology Institute of Slovenia for the days of the experiment. The data was collected by the oceanographic buoy “Vida” moored near Piran at coordinates (N 45° 32' 55,68", E 13° 33' 01,89").

5.3.1 – Weather Conditions on 17 May 2010

The two spaceborne SAR images acquired on 17 May 2010 are a TerraSAR-X-Spotlight by 5:27 UTC and a Radarsat2-Spotlight acquired by 17:10 UTC. Figure 19 shows the Sigma Naught (σ°) of the first spaceborne SAR image acquired on 17May 2010 by 05:27AM and a photo of the sea at the approximate time of the satellite pass. The weather conditions at the time of the satellite pass are given in Table 9.

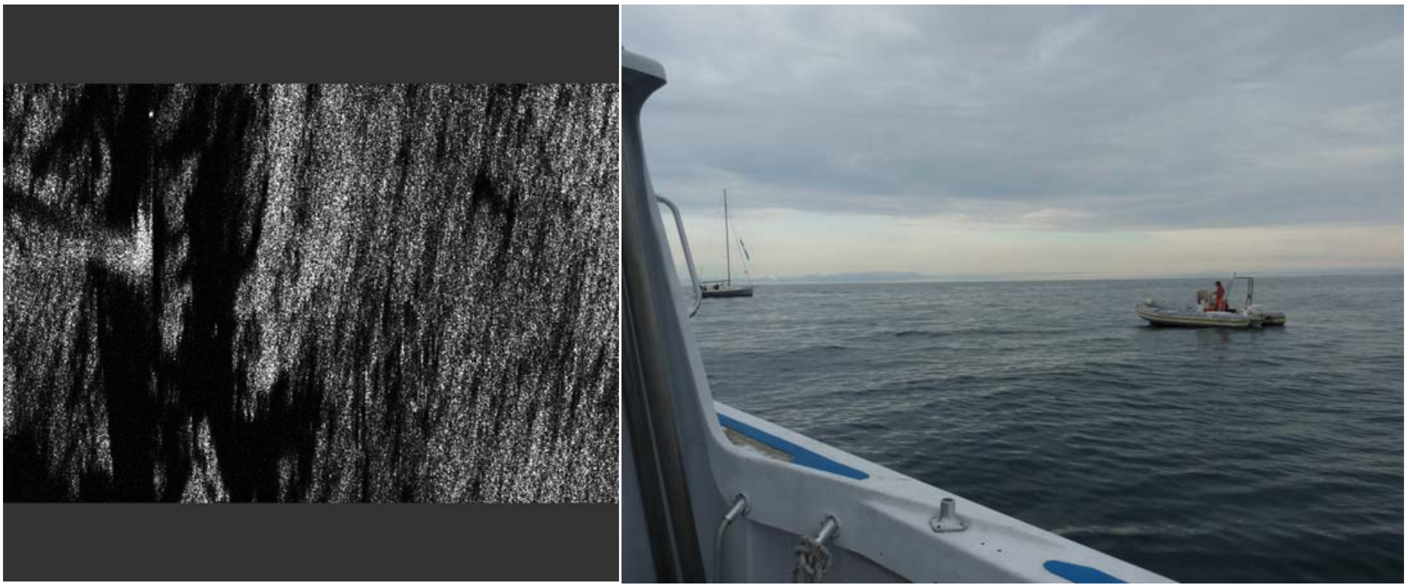


Figure 19 – TSX1_SAR_Spotlight -17May2010 (T 05:27:09 UTC) and a photo of the area at the time of the Satellite pass.

This is the image where the SAR signatures of the targets are more difficult to identify since they are not as clearly seen as in the remaining SAR images acquired during the experiment. There are several possible explanations for that. The spaceborne SAR image shows some clutter and artifacts which are not uniformly distributed over the area of the image. Apparently, the main reason to explain the aspect of the image is the relatively low incidence angle (about 20°), which is the lower limit of the full performance incidence angle range for TerraSAR-X.

Another possible reason for the clutter pattern displayed by the image seems to be the relatively high wave mean period (lower frequency) making difference between the clutter due to gravity and capillary waves more evident. The gust wind speed and direction also seems to play a role mainly on the sea clutter due to capillary waves.

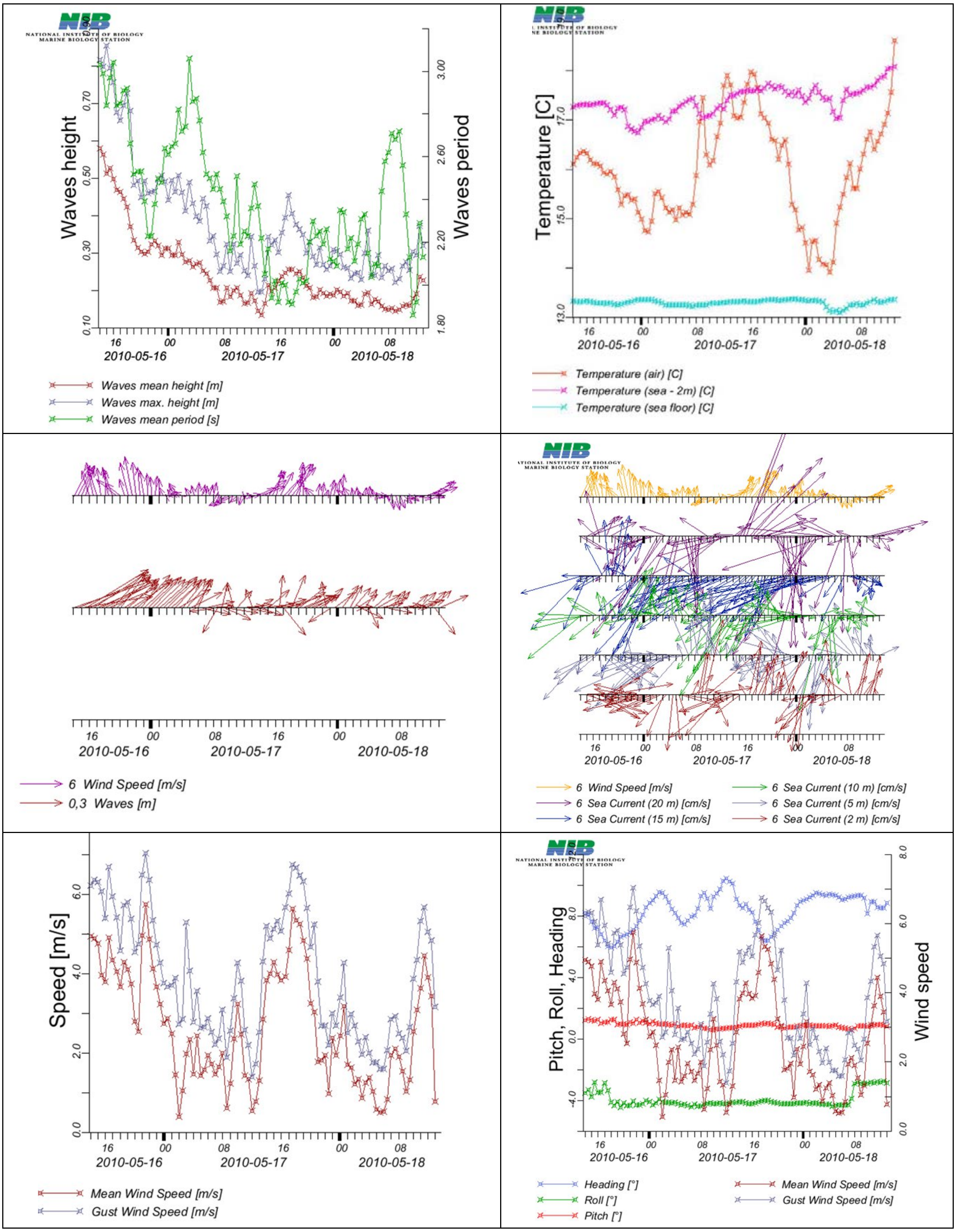


Table 9 – Weather conditions at the approximate time of the satellite pass (17May2010 (T 05:27:09 UTC)).

Figure 20 shows the Sigma Naught (σ°) of the second spaceborne SAR image acquired on 17May 2010 by 17:10 UTC and a photo of the sea at the approximate time of the satellite pass. The weather conditions by the time of the satellite pass are given in Table 9.

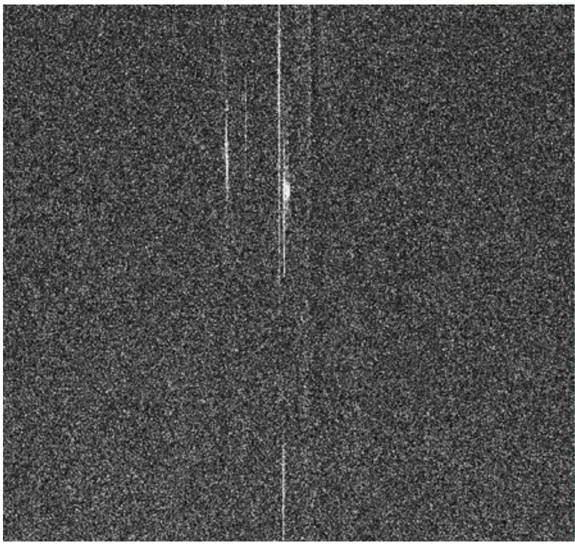



Figure 20 – RS2_SAR_Spotlight -17May2010 (T17:10:51 UTC) and a photo of the area at the time of the Satellite pass.

The sea clutter in this image seems to have a more uniform distribution and the SAR signatures of the targets are easier to identify. The relatively high incidence angle seems to improve the SAR signatures (about 49°). At the time of the satellite pass the wave mean period was significantly lower (higher frequency) than in the first image. The gust wind speed and the mean wind speed are significantly higher than at the time of acquisition of the first image. This seems to generate more capillary waves and therefore increase the sea clutter due to capillary waves.

5.3.2 – Weather Conditions on 18 May 2010

The only spaceborne SAR image acquired on 18 May 2010 was a TerraSAR-X-Spotlight by 05:10 UTC. Figure 21 shows the Sigma Naught (σ°) of the spaceborne SAR image acquired on 18May 2010 by 05:10 UTC and a photo of the sea at the approximate time of the satellite pass. The weather conditions at the time of the satellite pass are given in Table 10.

Analysing the weather conditions given in Table 10, it can be seen that the wave mean period is moderate and the gust wind speed and the mean wind speed are relatively low. It seems that these two conditions lead to relatively low sea clutter, in particular sea clutter due to capillary waves. The incidence angle was about 48°.

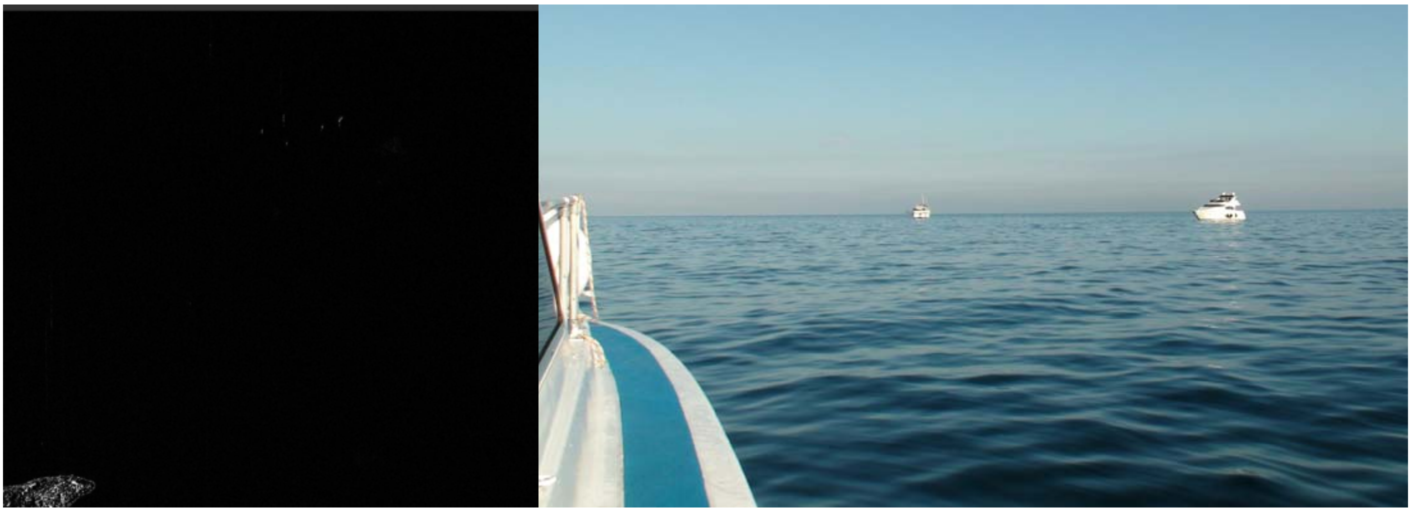
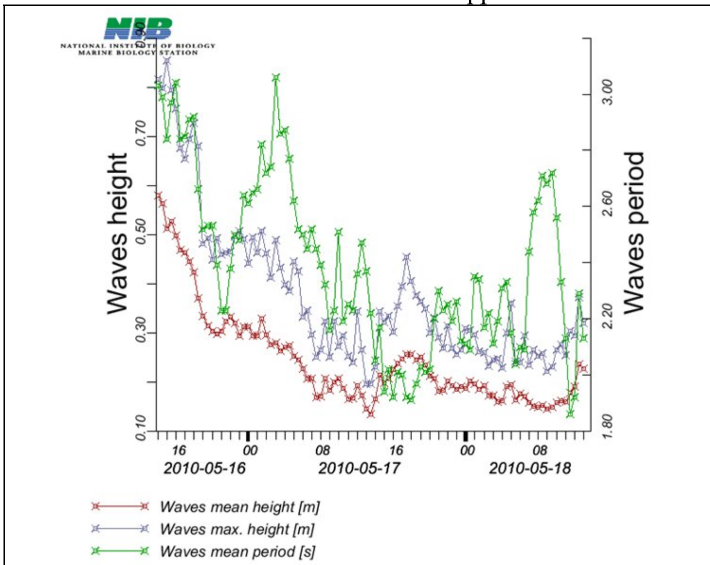
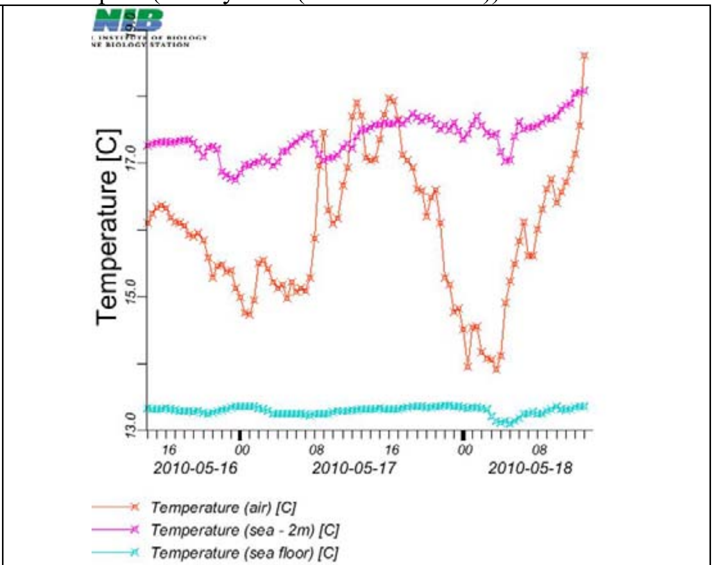
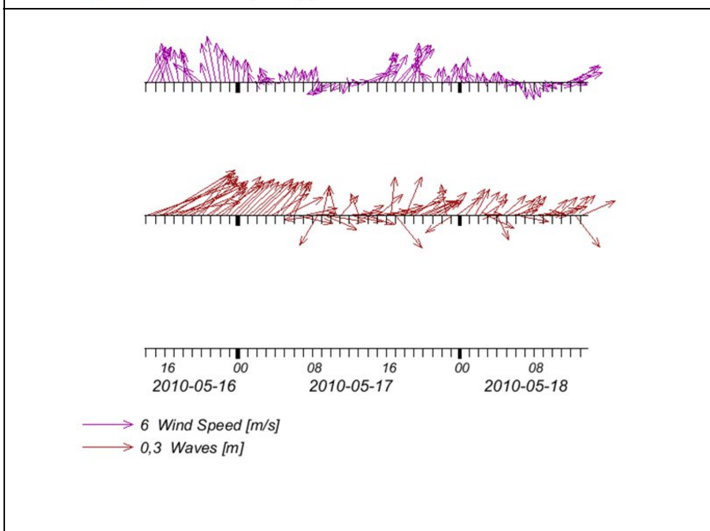


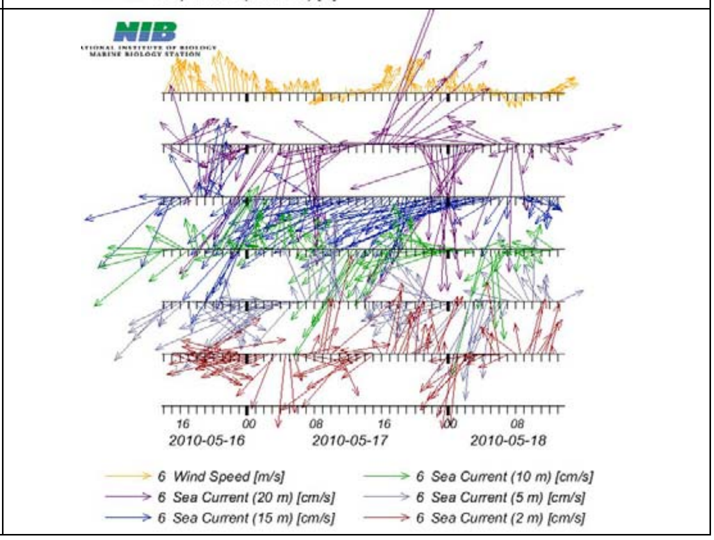
Figure 21 – TSX1_SAR_Spotlight -18May2010 (T 05:10:02 UTC) and a photo of the area at the time of the Satellite pass.

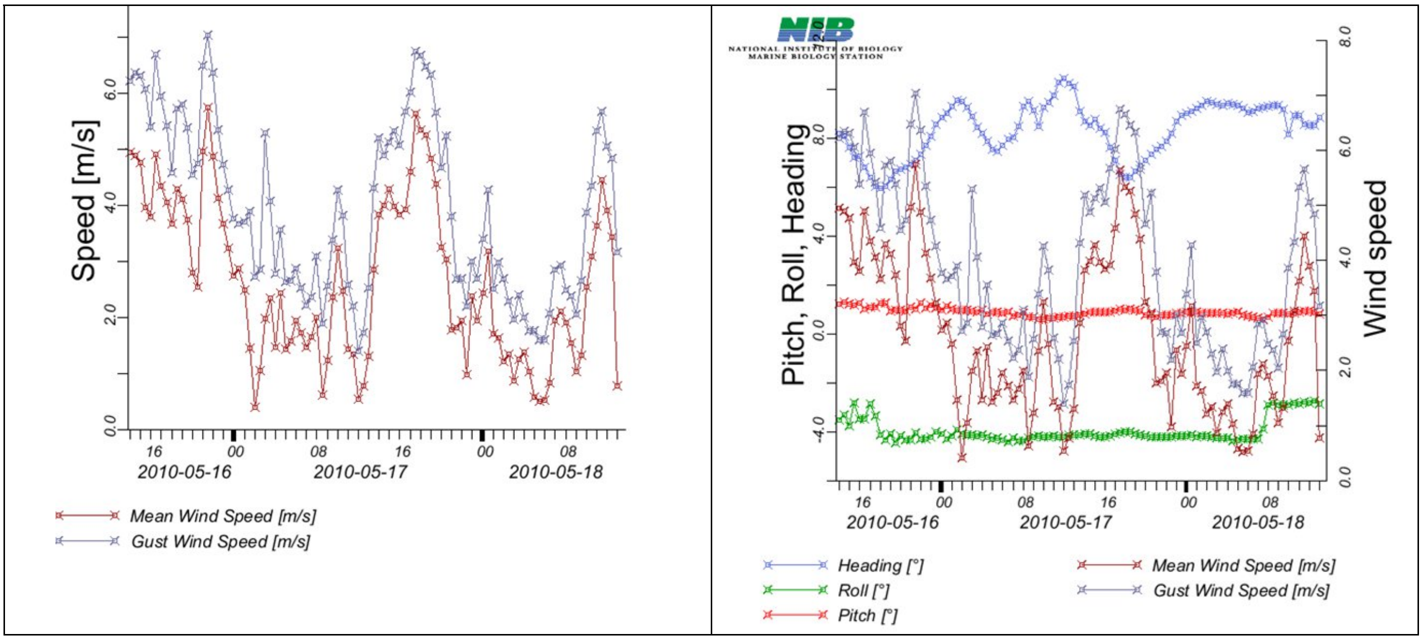
Table 10 – Weather conditions at the approximate time of the satellite pass (18May2010 (T 05:10:02 UTC)).











5.3.3 – Weather Conditions on 31 May 2010

The two spaceborne SAR images acquired on 31 May 2010 are a TerraSAR-X-Spotlight by 16:50 UTC (Fig. 22) and a Radarsat2-Spotlight acquired by 17:02 UTC (Fig.23). Figures 22 and 23 show the Sigma Naught (σ°) of the two spaceborne SAR images acquired on 31 May 2010 by and a photo of the sea at the approximate time of the satellite pass. The weather conditions at the time of the satellite pass are given in Table 11.

The incidence angles of the two spaceborne SAR images are about 32° and 41°, respectively. Although the two images were acquired just about 12 minutes apart they display different sea clutter and artifacts.

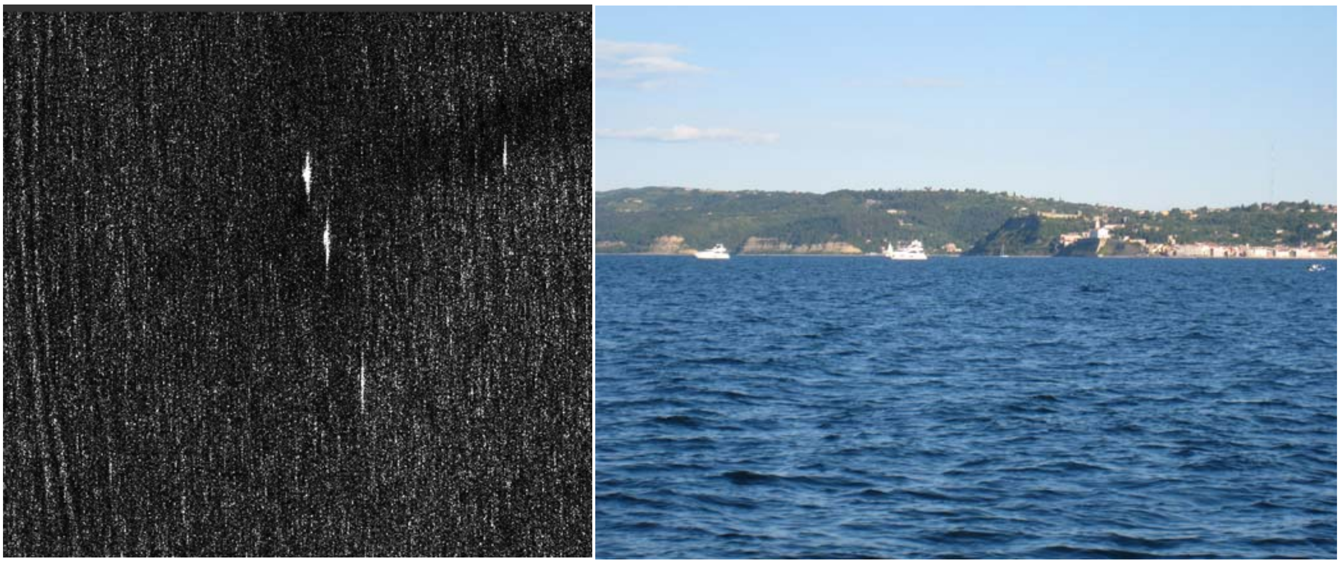


Figure 22 – TSX1_SAR_Spotlight -31May2010 (T 16:50:46 UTC) and a photo of the area at the time of the Satellite pass.

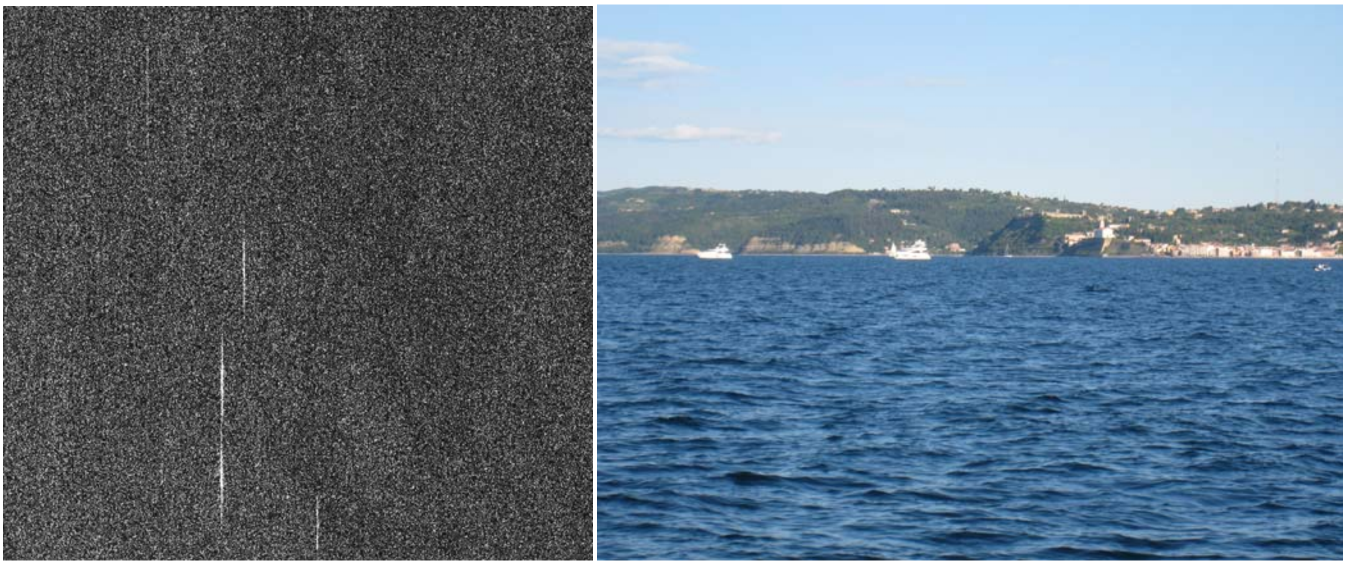
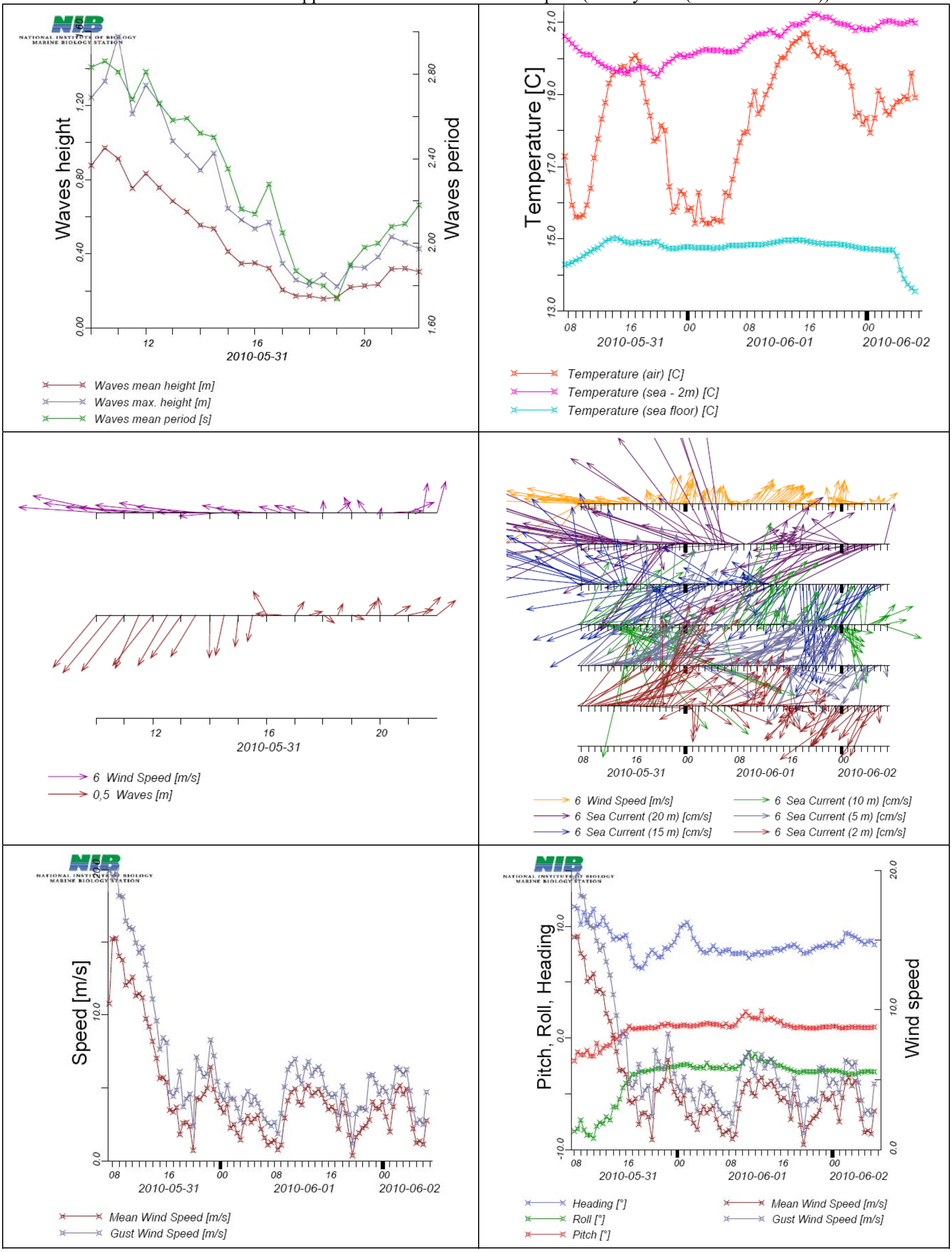


Figure 23 – RS2_SAR_Spotlight -31May2010 (T 17:02:32 UTC) and a photo of the area at the time of the Satellite pass.

Table 11 – Weather conditions at the approximate time of the satellite pass (31May2010 (T 16:50:46 UTC)).



5.3.4 – Weather Conditions on 01 June 2010

The only spaceborne SAR image acquired on 01 June 2010 was a RS2_SAR_Ultrafine (T 05:13:03 UTC). Figure 24 shows the Sigma Naught (σ°) of the spaceborne SAR image acquired on 01 June 2010 by 05:13 UTC. The weather conditions at the time of the satellite pass are given in Table 12.

Analysing the weather conditions given in Table 12, it can be seen that the wave mean period, the gust wind speed and the mean wind speed are relatively high. This seems to explain the relatively high sea clutter displayed by the image in Fig. 24. The incidence angle was about 38°.

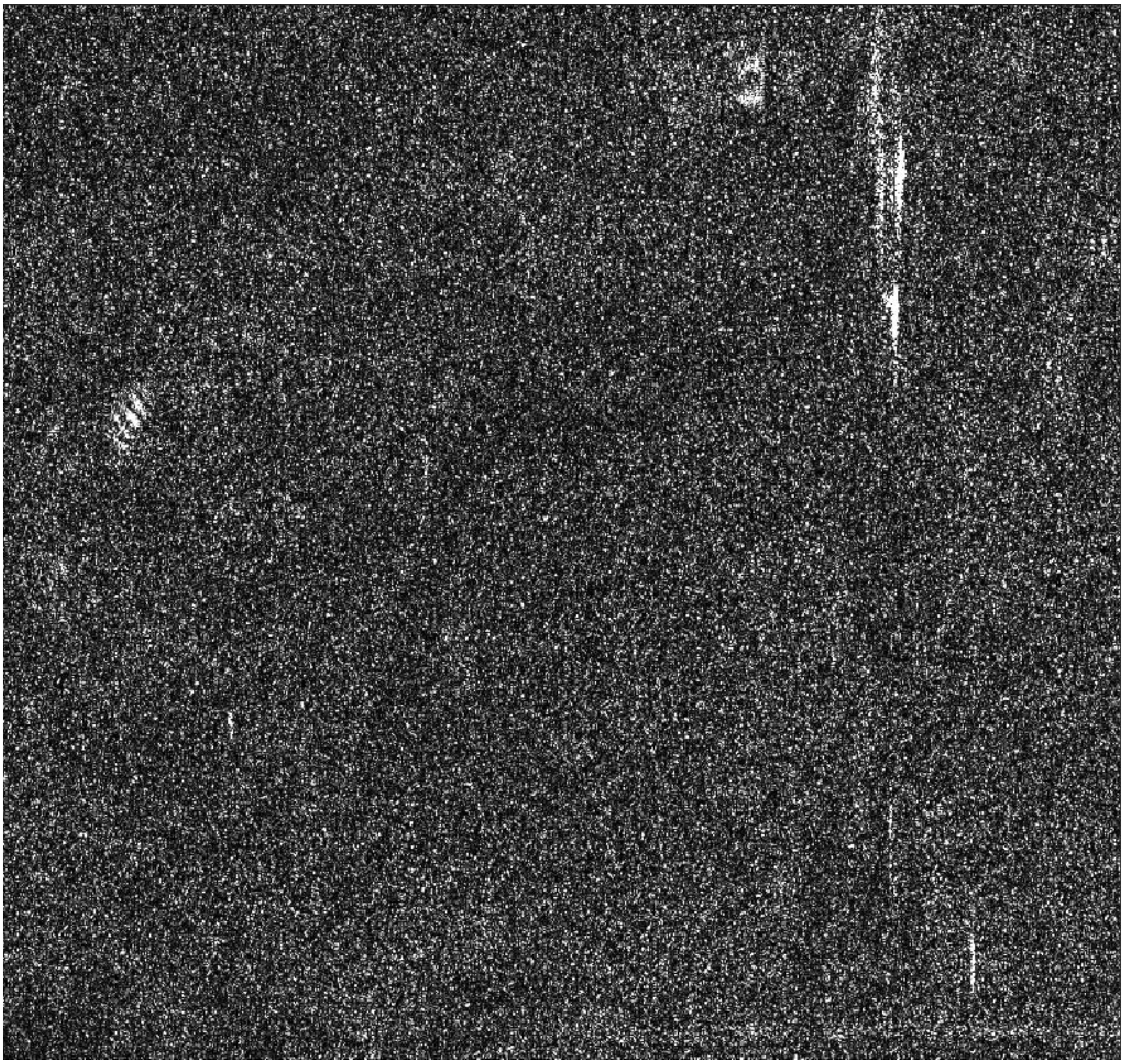
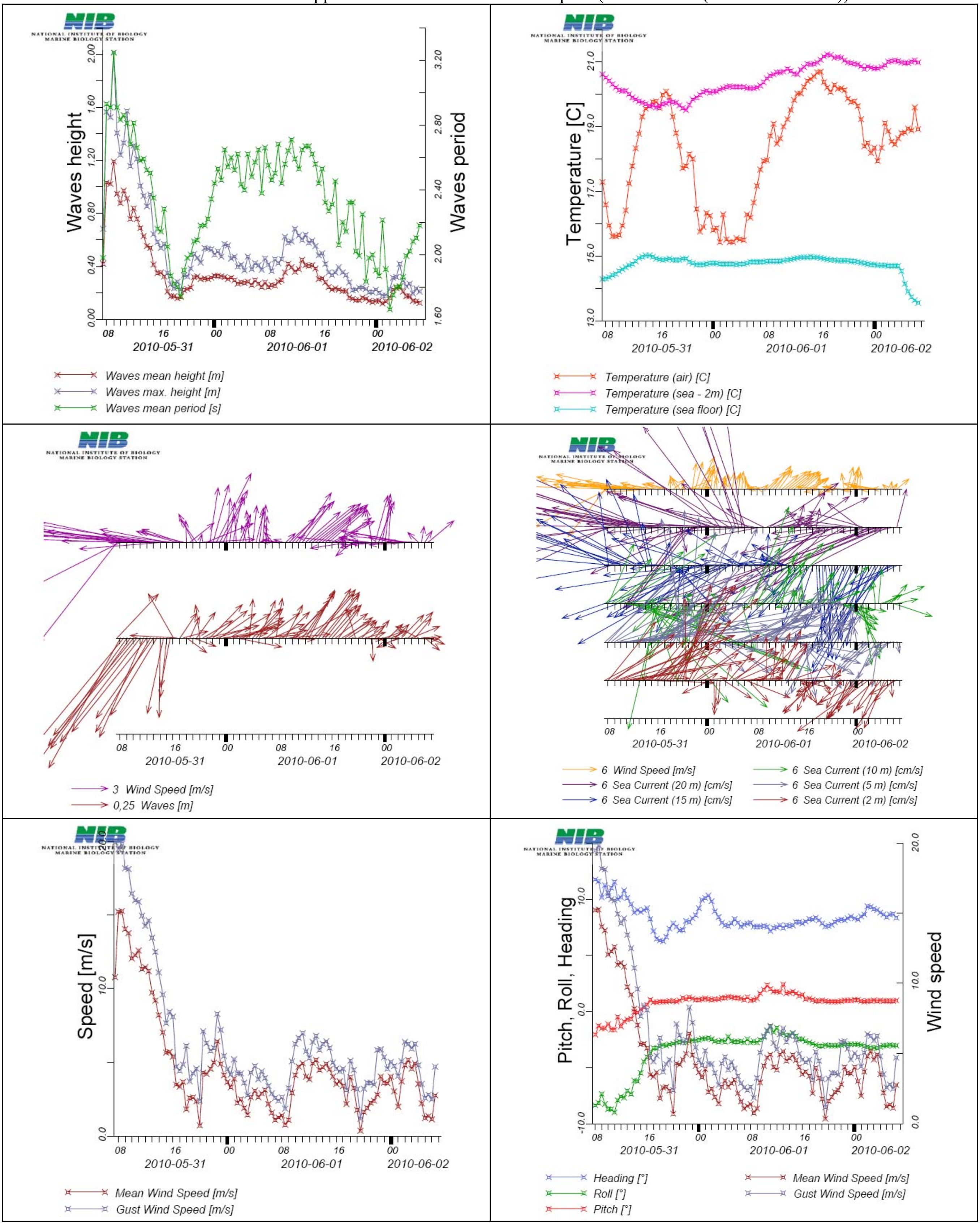


Figure 24 – RS2_SAR_Ultrafine - 01June2010 (T 05:13:03UTC)

Table 12 – Weather conditions at the approximate time of the satellite pass (01June2010 (T 05:13:03 UTC)).



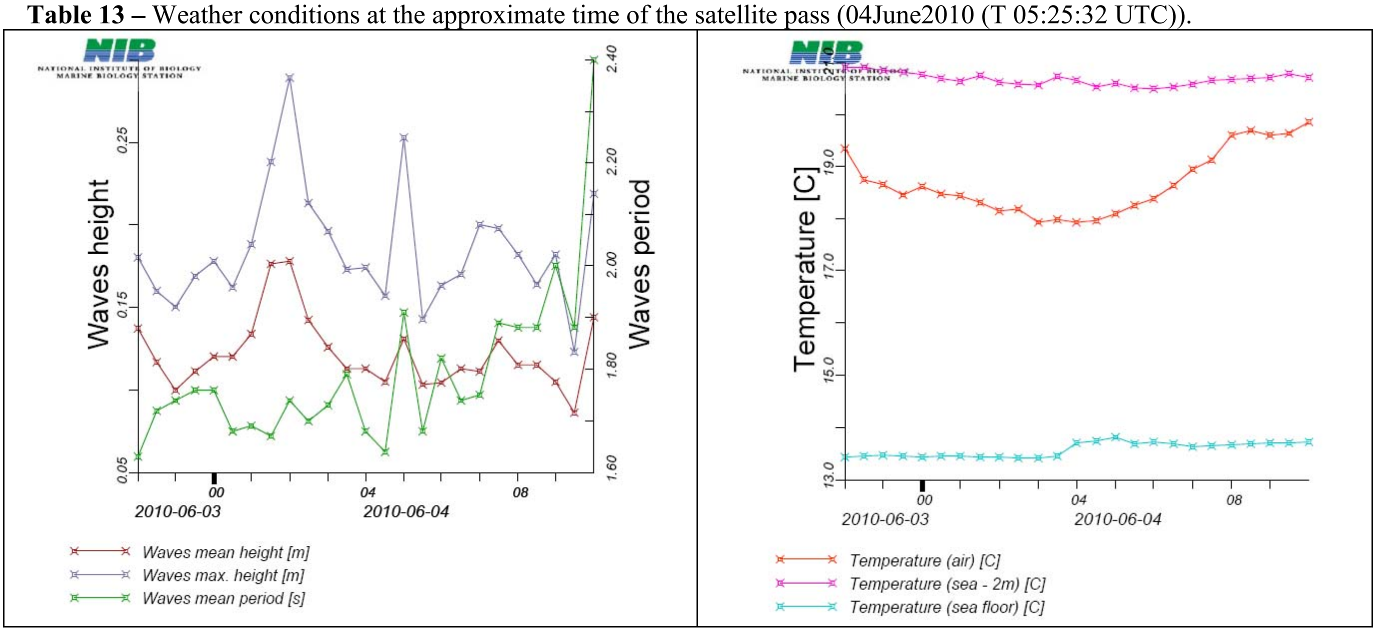
5.3.5 – Weather Conditions on 04 June 2010

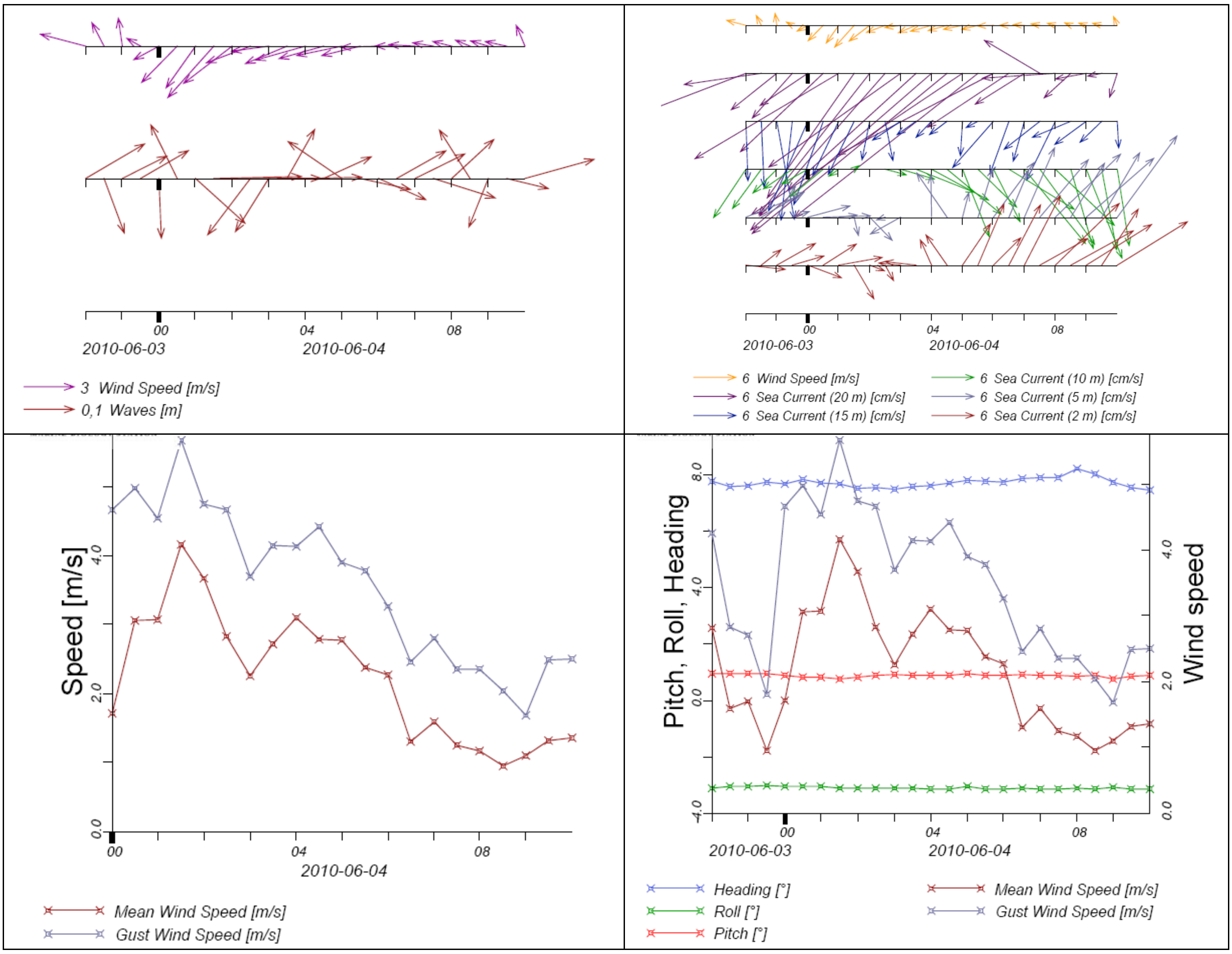
The only spaceborne SAR image acquired on 04 June 2010 was a RS2_SAR_Spotlight (T 05:25:32 UTC). Figure 25 shows the Sigma Naught (σ°) of the spaceborne SAR image acquired on 04 June 2010 by 05:32 UTC. The weather conditions at the time of the satellite pass are given in Table 13.

Analysing the weather conditions given in Table 13, it can be seen that the wave mean period, the gust wind speed and the mean wind speed are moderate. This seems to explain the relatively low sea clutter displayed by the image in Fig. 25. The incidence angle was about 25°.

Figure 25 – RS2_SAR_Spotlight -04June2010 (T 05:25:32 UTC) and a photo of the area at the time of the Satellite pass.

Table 13 – Weather conditions at the approximate time of the satellite pass (04June2010 (T 05:25:32 UTC)).




00
04
08
2010-06-03
2010-06-04
3 Wind Speed [m/s]
0,1 Waves [m]
6 Wind Speed [m/s]
6 Sea Current (20 m) [cm/s]
6 Sea Current (15 m) [cm/s]
6 Sea Current (10 m) [cm/s]
6 Sea Current (5 m) [cm/s]
6 Sea Current (2 m) [cm/s]
Speed [m/s]
0.0
2.0
4.0
Mean Wind Speed [m/s]
Gust Wind Speed [m/s]
Pitch, Roll, Heading
Wind speed
-4.0
0.0
4.0
8.0
Heading [°]
Roll [°]
Pitch [°]

5.4 – Verification of the Results

Table-14 gives a summary of all SAR images acquired during the maritime surveillance campaign in Portoroz-Slovenia from 17.May.2010 to 04Jun.2010. The table gives the date and time of acquisition, the place, the Satellite image mode and the ground truth data collected. The boat detections are all based on a visual analysis of the SAR images.

Table 14 – List of SAR Satellite Images acquired during the experiment.

Date / Time	Place	Satellite / Mode	Ground Truth Data
17.May.2010 (AM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	GPS/Photos/Movies
17.May.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	“ “
18.May.2010 (AM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	“ “
31.May.2010 (PM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	“ “
31.May.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	“ “
01.Jun.2010 (AM)	Portoroz- Slovenia	Radarsat-2 / Ultrafine	“ “
04.Jun.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	“ “

The next sections give the comparison of each Synthetic Aperture Radar (SAR) image with the ground truth data collected during the experiment, namely the GPS coordinates of each boat and the photos and videos. The outcome of a visual inspection and analysis of the SAR images is described.

As it can be seen in the next sections, apart the first image where the identification of the SAR signatures of the boats deployed as targets is not straightforward, in all other images all the boats were detected.

The visual analysis takes into account the GPS positions, photos, videos and the weather conditions, including the sea state, the wind speed, and the wave height and period.

5.4.1 – TerraSAR-X-Spotlight, 17May2010 (5:27AM UTC), Portoroz-Slovenia

Figure 26 illustrates the relative positions of the different boats involved in the experiment on 17May2010 AM. At the approximate time of the satellite pass 5 boats were deployed nearby the oceanographic buoy (Vida) indicated in red in the same figure. The yacht Dominator-II was travelling from Izola towards the oceanographic buoy.

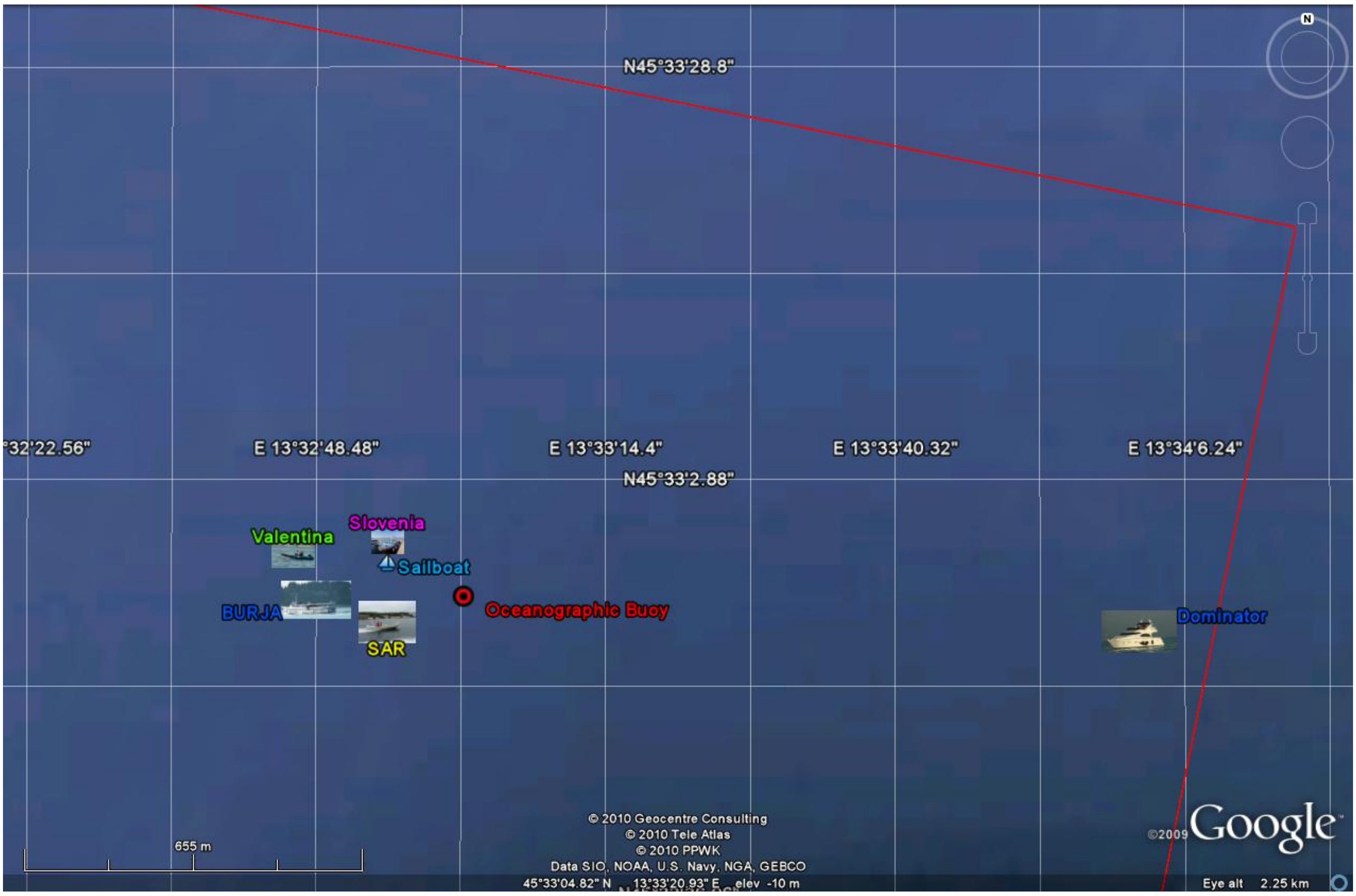


Figure 26 – 17May2010 (05:27UTC). On the left, a set of 5 boats deployed nearby the oceanographic buoy and on the right, the yacht Dominator-II travelling from Izola towards the oceanographic buoy. In red, we can see part of the footprint of the spaceborne SAR image.

Figure 27 shows a subset of the TerraSAR-X-Spotlight image (17May2010 – 05:27UTC) with the relative position of the boats indicated. The identification of the SAR signatures of the boats deployed is not straightforward because the SAR signatures are relatively weak and hardly can be isolated from the sea clutter. The only SAR signature that appears as a bright spot is the one from Dominator II. Some possible reasons for such weak SAR signatures include the relatively low incidence angle and the weather conditions at the time of the satellite pass. The incidence angle was about 20°, which is the lower limit of the full performance incidence angle range for TerraSAR-X.

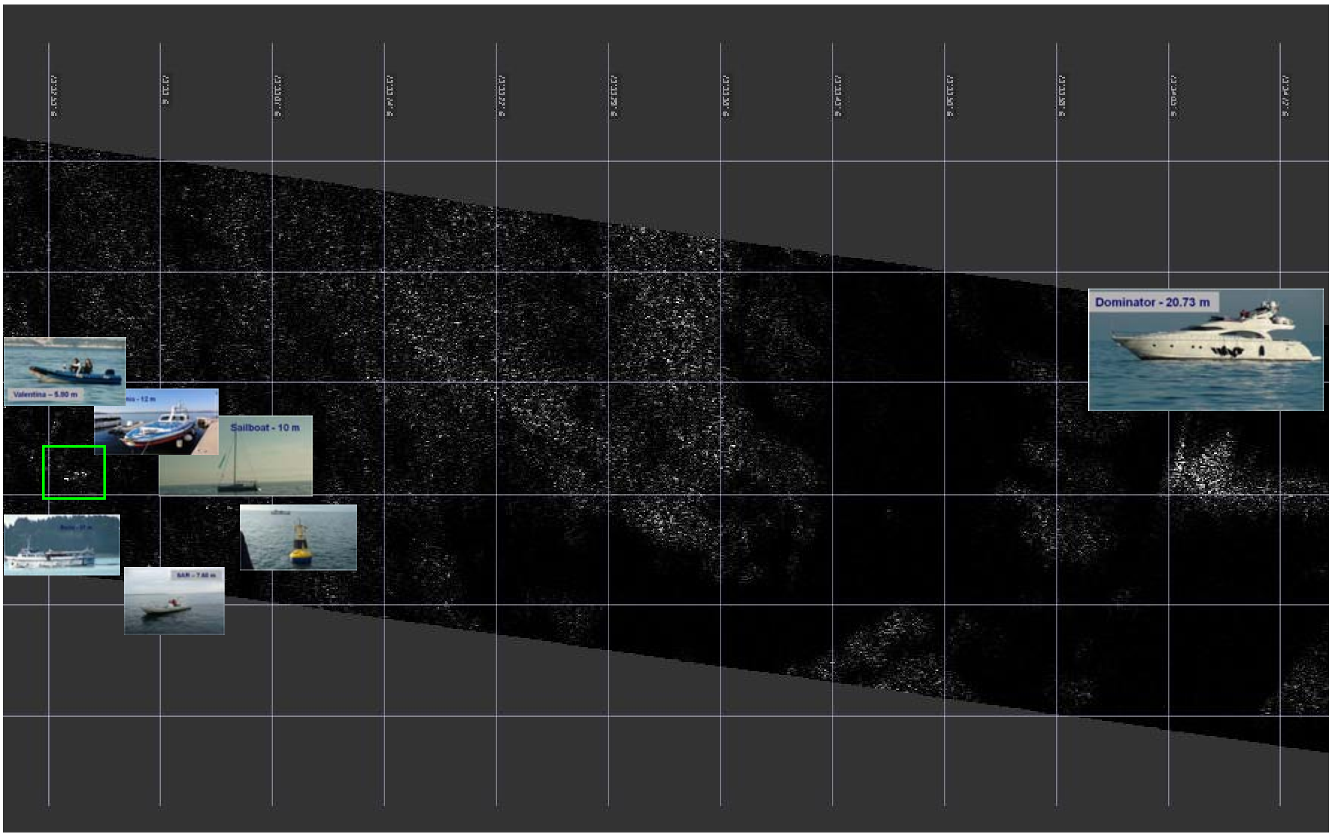


Figure 27 – Relative position of the boats over the reprojected TerraSAR-X-Spotlight image 17May2010.

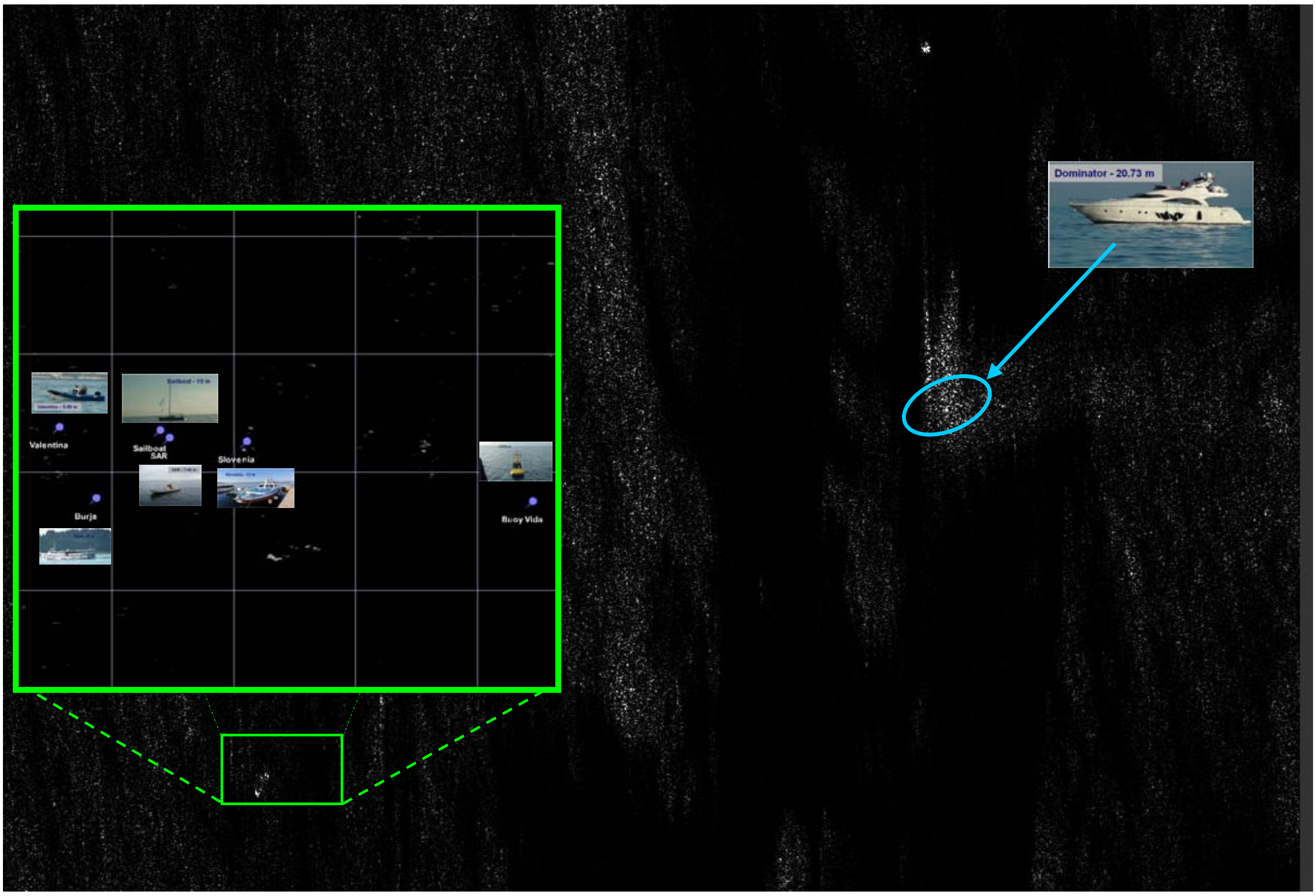


Figure 28 – Zoo-in of the SAR signatures of the cluster of 5 boats.

5.4.2 – Radarsat2-Spotlight, 17May2010 (17:10AM UTC), Portoroz-Slovenia

Figure 29 illustrates the relative positions of the different targets in the Radarsat-Spotlight image (17May2010 – 17:10UTC) and their SAR signatures. All the boats deployed were detected in the SAR images. The SAR signatures of the rubber boat (Valentina) and the sailboat were weaker than expected. The SAR signature of the oceanographic buoy (Vida) is significantly strong. This seems to be due to the mast effect. The sea clutter is relatively strong but the SAR signature of most targets can clearly be identified.

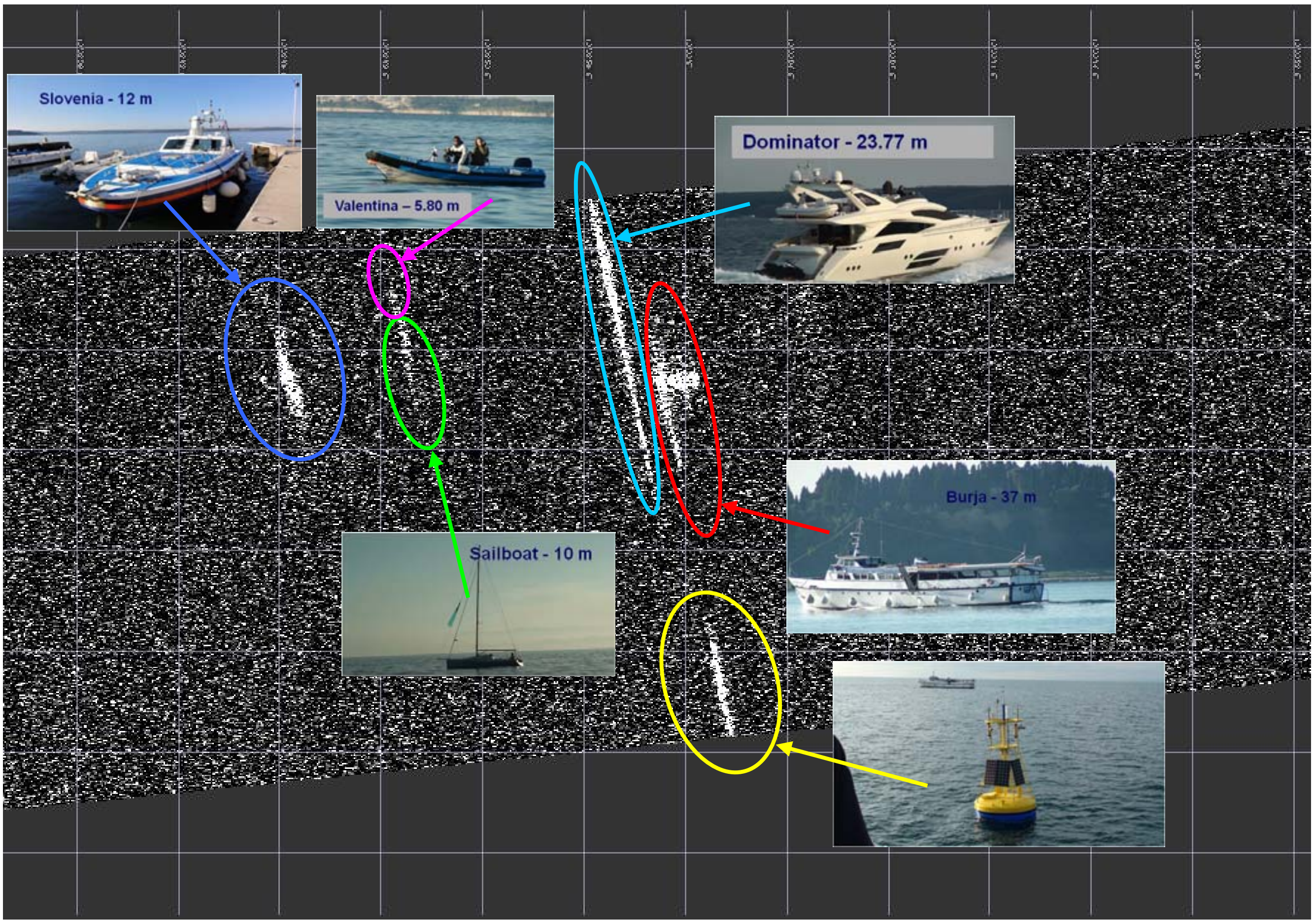


Figure 29 – Identification of the different targets deployed and their corresponding SAR signatures.

5.4.3 – TerraSAR-X-Spotlight, 18May2010 (5:10AM UTC), Portoroz-Slovenia

Figure 30 shows the SAR signatures of the boats deployed as targets, as well as their relative positions in several photos taken at the time of the satellite pass (TerraSAR-X-Spotlight) (18May2010 – 05:10UTC) .

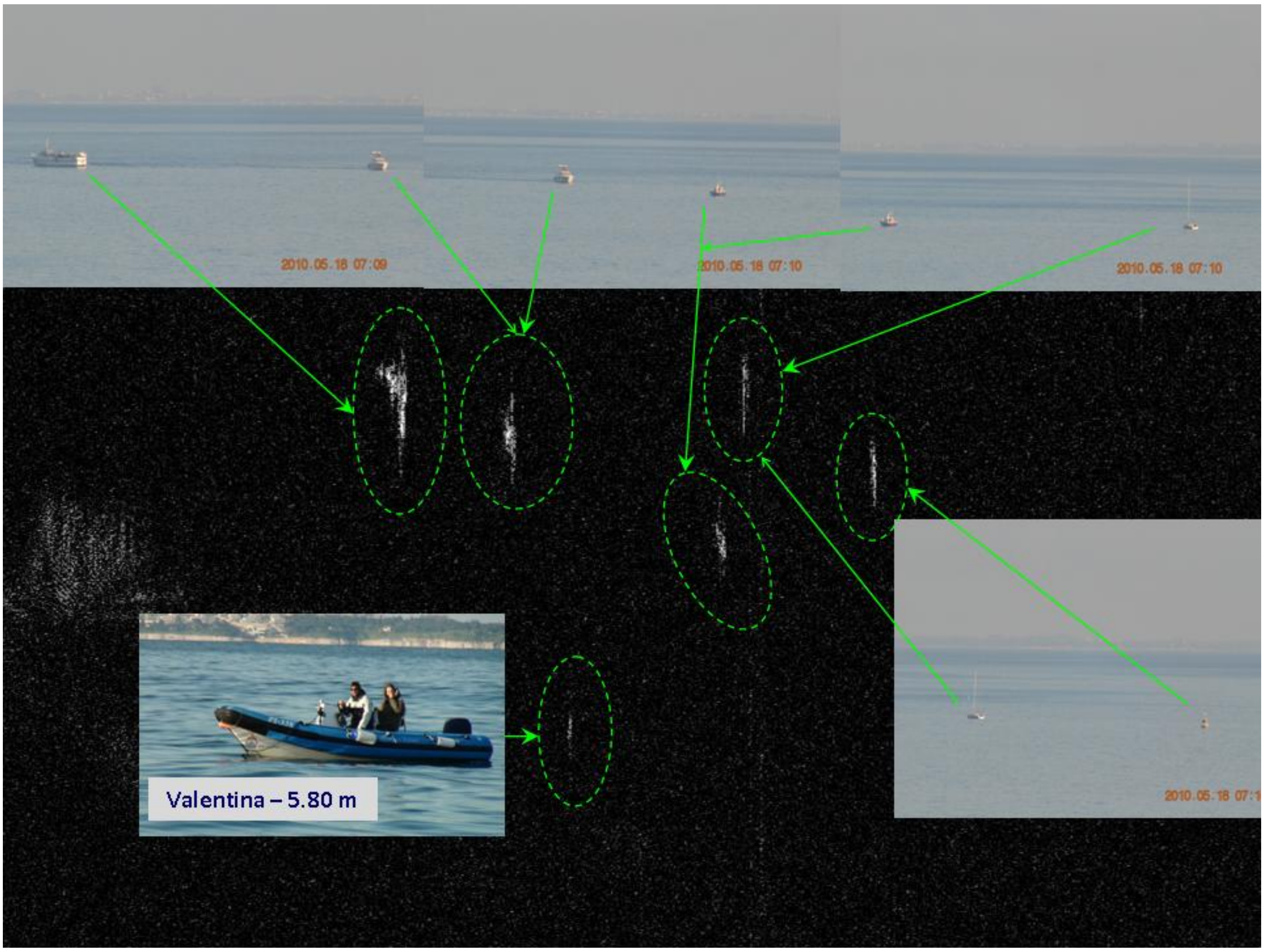


Figure 30 – SAR signatures of the 5 boats deployed as targets. The oceanographic buoy was also detected.

In this SAR image the SAR signatures of the targets can clearly be identified. Even the smallest rubber boat deployed (Valentina, 5.8m) has a relatively strong SAR signature. Also the sea clutter is low. Some possible explanations for the easy identification of these SAR signatures include the incidence angle of the SAR Satellite (about 49°) and the low wind speed and sea state, as well as the low wave height.

Figure 31 shows the SAR signatures of the boats deployed as targets, as well as zoomed-in photos of the boats used as targets. The SAR signatures of all targets are relatively strong, even those of the smallest targets, such as the oceanographic buoy and the small rubber boat Valentina.

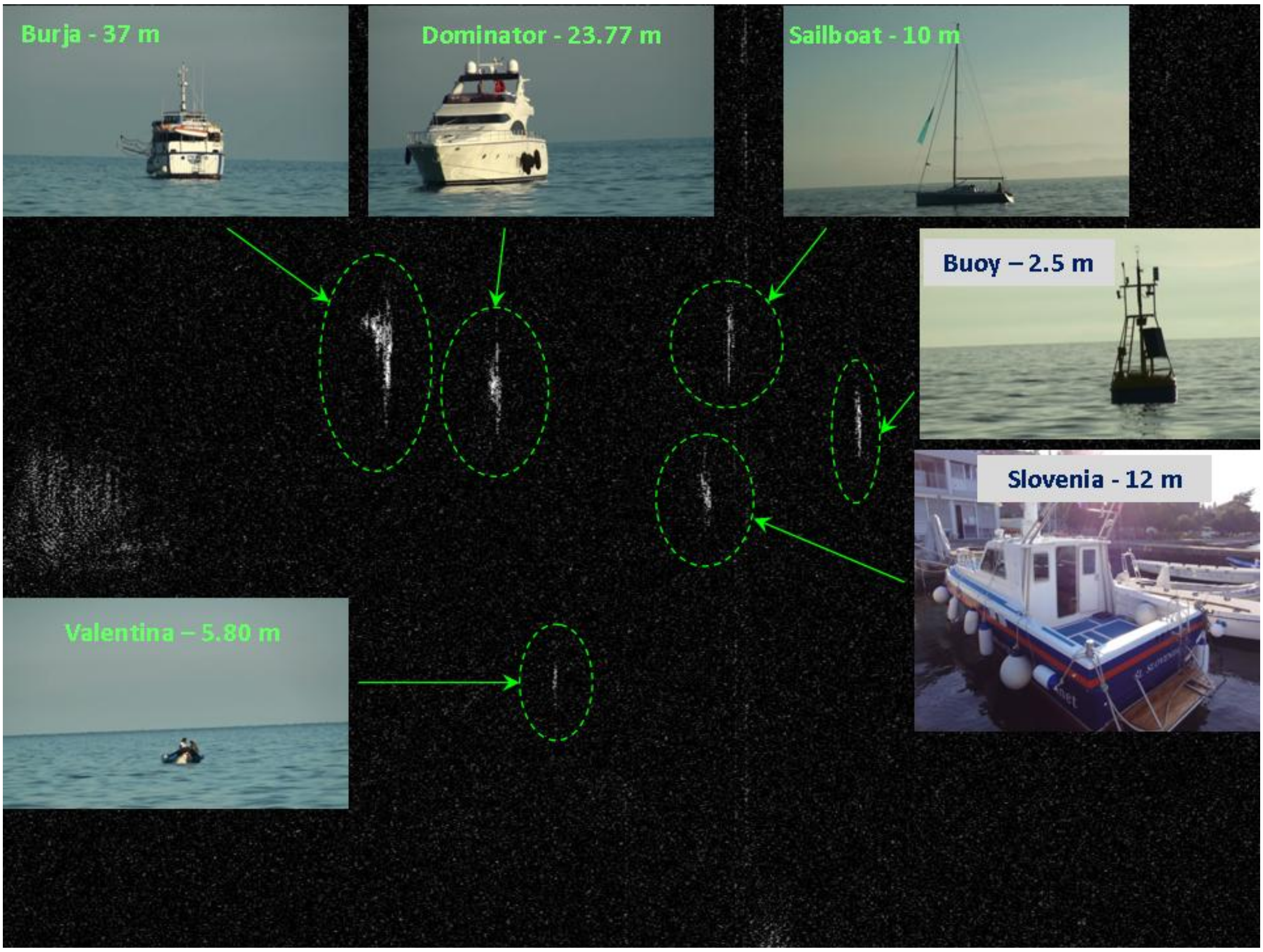


Figure 31 – The same spaceborne SAR image with larger photos of the boats used as targets.

5.4.4 – TerraSAR-X-Spotlight, 31May2010(16:50 UTC),Portoroz-Slovenia

Figure 32 shows the SAR signatures of the boats deployed as targets, as well as the photos of the boats used as targets at the time of the satellite pass (TerraSAR-X-Spotlight) (31May2010 – 16:50UTC) .

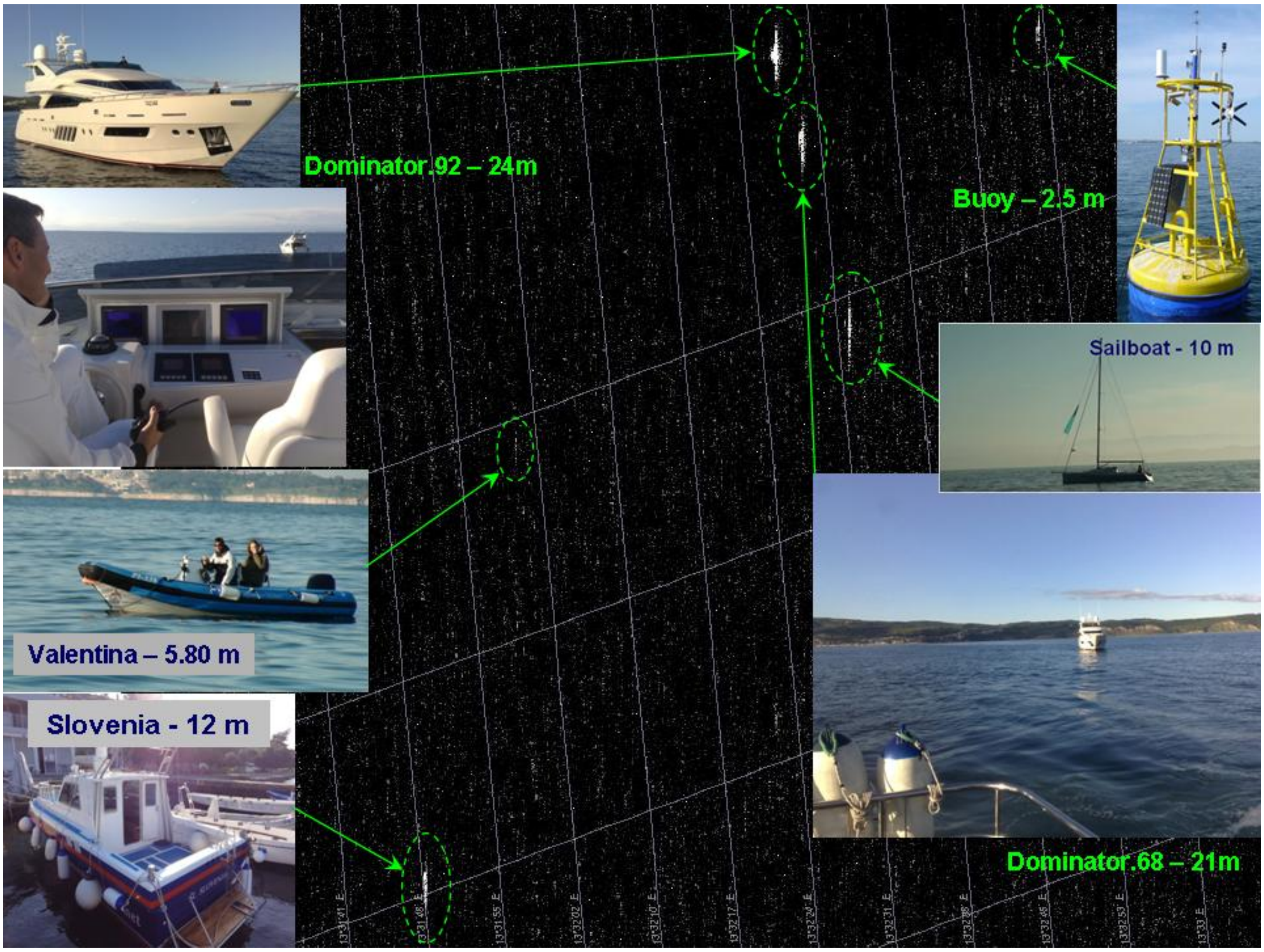


Figure 32 – Photos of the boats used as targets and their spaceborne SAR signatures.

In this SAR image the SAR signatures of the targets can be identified. The smallest rubber boat deployed (Valentina, 5.8m) has a relatively weak SAR signature. The sea clutter is low. Some possible explanations for the easy identification of these SAR signatures include the incidence angle of the SAR Satellite (about 32°) and the low wind speed and sea state, as well as the low wave height.

5.4.5 – Radarsat2-Spotlight, 31May2010 (17:02UTC), Portoroz-Slovenia

Figure 33 shows the SAR signatures of the boats deployed as targets, as well as photos of the boats used as targets at the time of the satellite pass (TerraSAR-X-Spotlight) (31May2010 – 17:02UTC) .

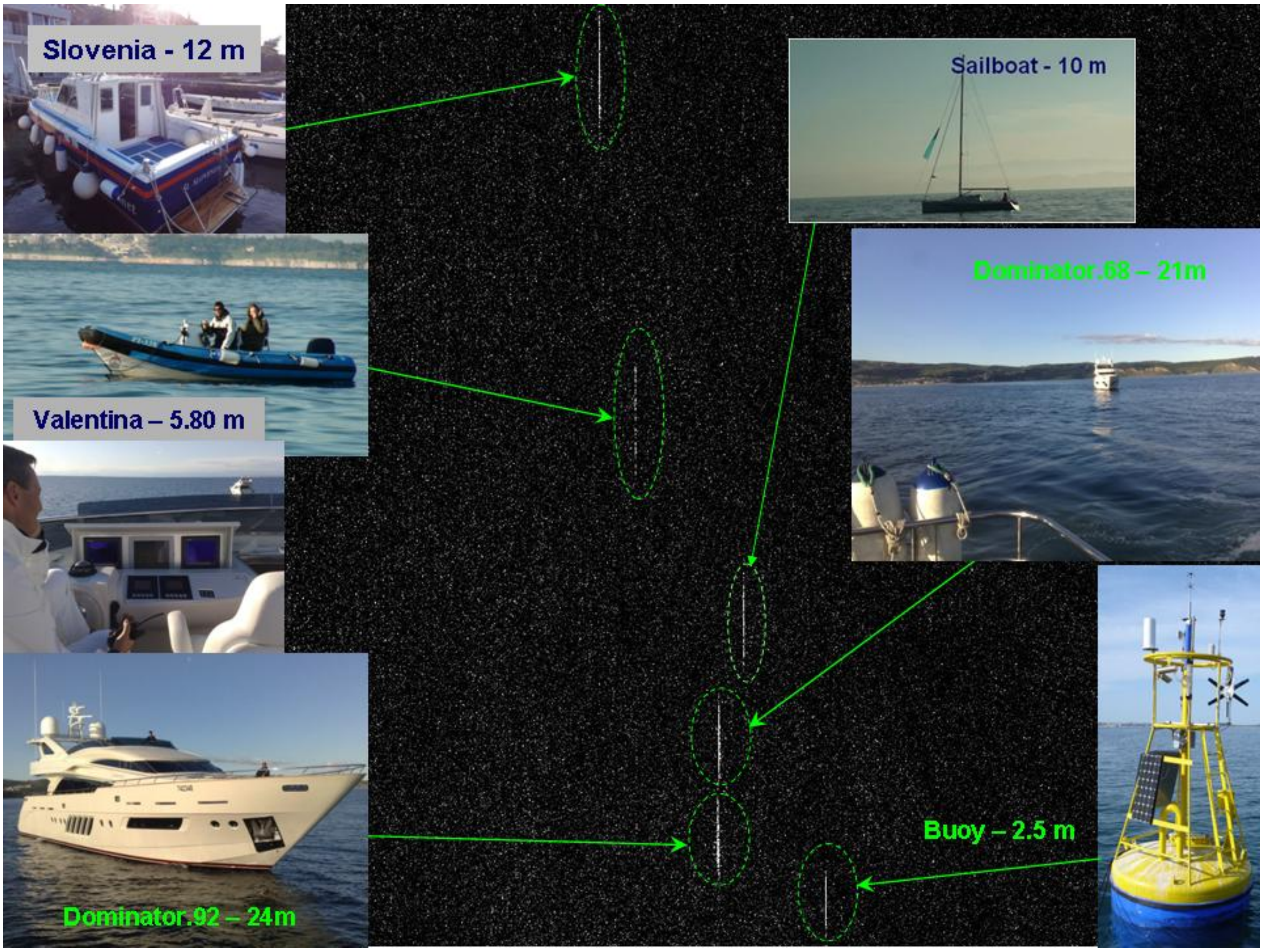


Figure 33 – Relative positions of the boats used as targets and their respective SAR signatures.

In this SAR image the SAR signatures of the targets can be identified. The smallest rubber boat deployed (Valentina, 5.8m) has a relatively weak SAR signature. The sea clutter is low. Some possible explanations for the easy identification of these SAR signatures include the incidence angle of the SAR Satellite (about 41°) and the low wind speed and sea state, as well as the low wave height.

5.4.6 – Radarsat2-Ultrafine, 01.Jun.2010 (05:13UTC), Portoroz-Slovenia

Figure 34 shows the SAR signatures of the boats deployed as targets, as well as their relative positions in several photos taken at the time of the satellite pass (RAdarsat2-Spotlight) (01Jun2010 – 05:13UTC)

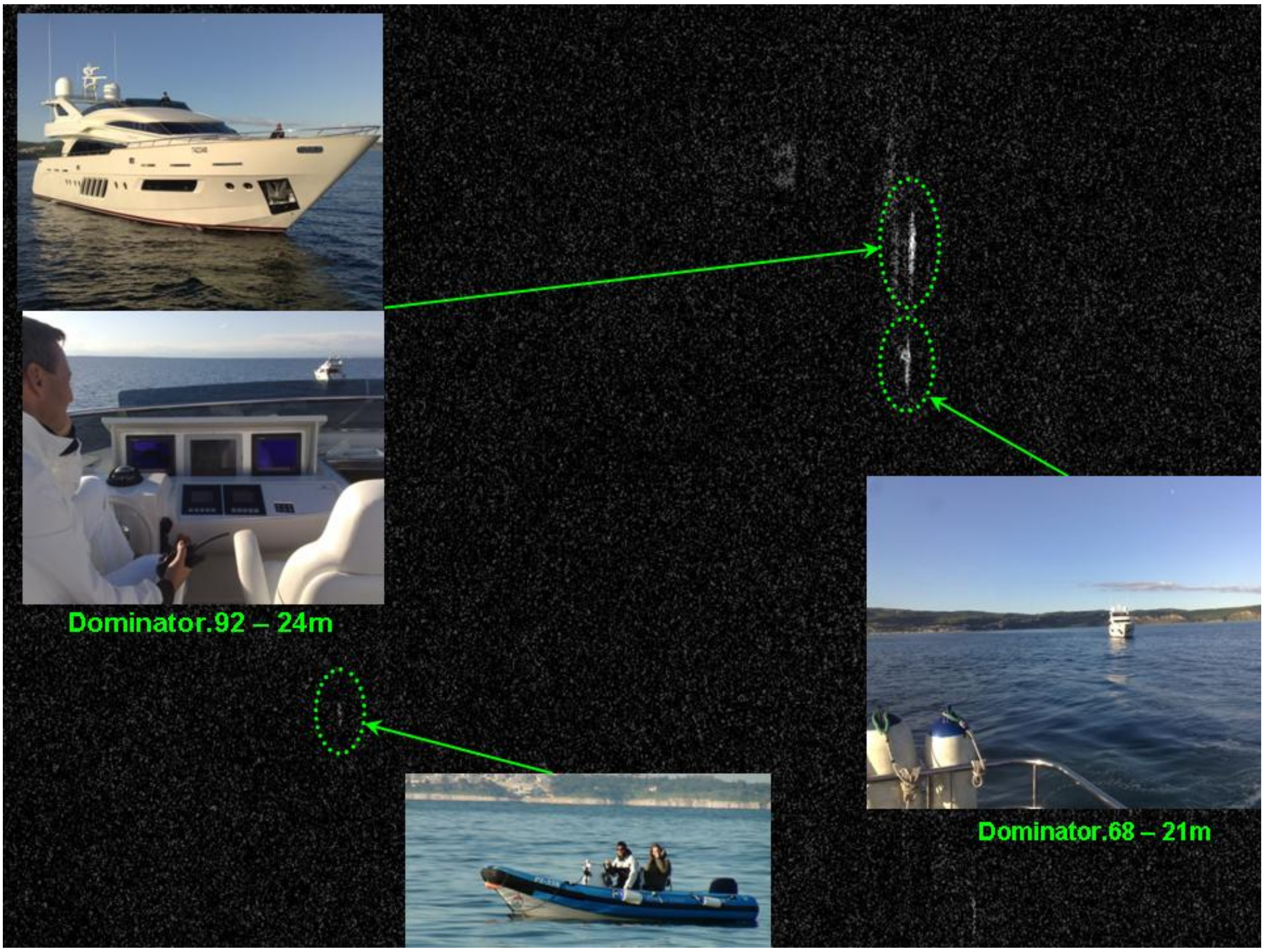


Figure 34 – Relative positions of the boats used as targets and their respective SAR signatures.

In this SAR image the SAR signatures of the larger targets can be identified. The smallest rubber boat deployed (Valentina, 5.8m) has a relatively weak SAR signature. The sea clutter is low. Some possible explanations for the easy identification of these SAR signatures include the incidence angle of the SAR Satellite (about 38°) and the low wind speed and sea state, as well as the low wave height.

5.4.7 – Radarsat2-Spotlight,04 June 2010(05:25UTC), Portoroz-Slovenia

Figure 35 shows the SAR signatures of the boats deployed as targets, as well as the photos of all the boats used as targets at the time of the satellite pass (Radarsat2-Spotlight) (01Jun2010 – 05:13UTC) .

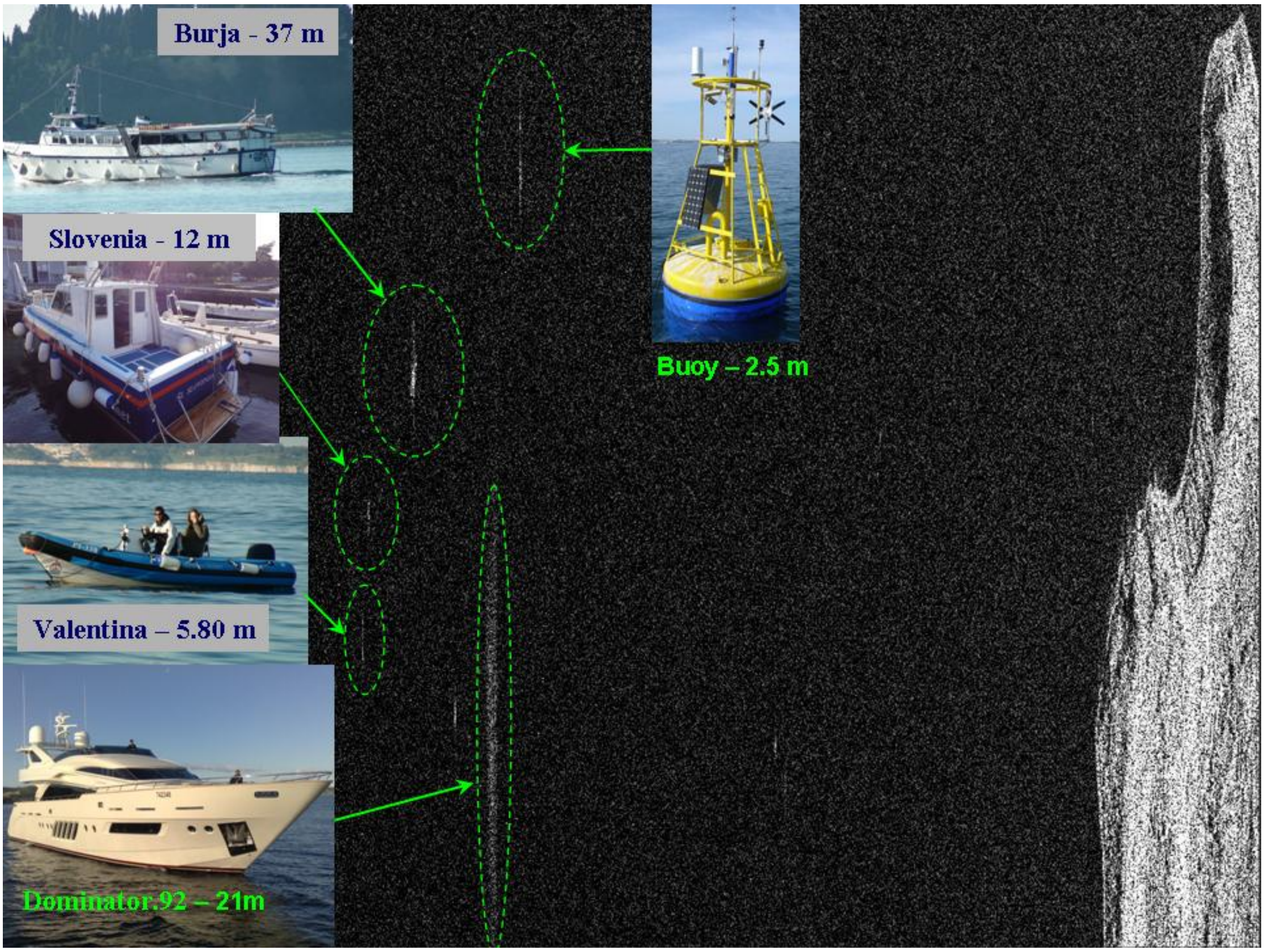


Figure 35 – Boats used as targets and their SAR signatures.

Analysing the weather conditions given in Table 13, it can be seen that the wave mean period, the gust wind speed and the mean wind speed are moderate. This seems to explain the relatively low sea clutter displayed by the image. The incidence angle was about 25°. The SAR signatures of some boats are relatively weake.

5.5 – Quantitative Analysis of the Spaceborne SAR Images

In order to allow a quantitative analysis of the data, all the spaceborne SAR images were calibrated using ESA's NEST software package, version 4B. The inputs were the SAR images acquired and the outputs were the Radiometric Calibration (Sigma Naught (σ°)) expressed in terms of intensity and in decibel (dB), the Radar Brightness (β°) and the Radiometric Normalisation (gamma naught (γ°)).

5.5.1 – TerraSAR-X-Spotlight, 17May2010 (5:27AM UTC), Portoroz-Slovenia

Figure 36 illustrates the Intensity band of the TerraSAR-X-Spotlgiht image (17May2010).

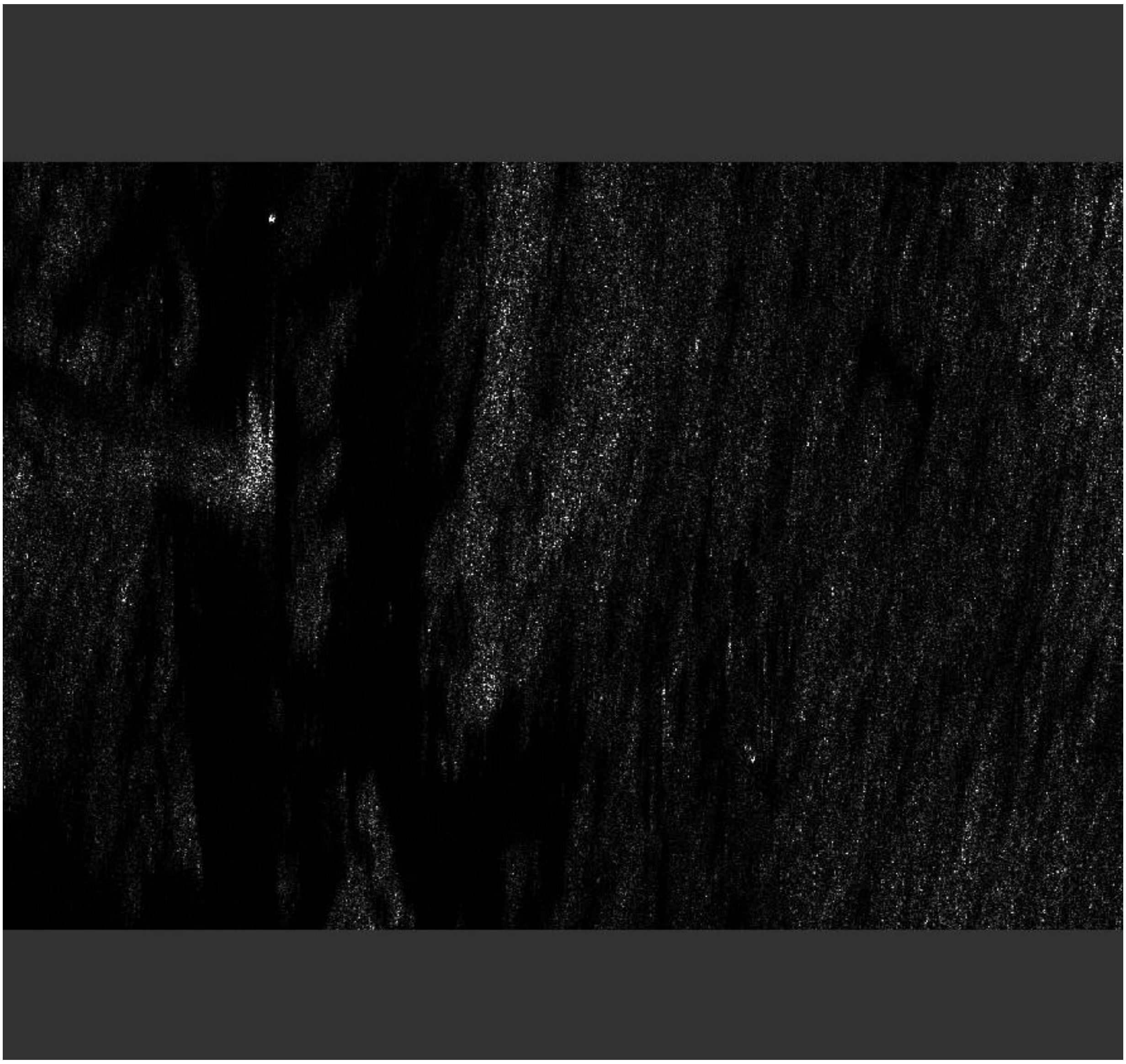


Figure 36 – TerraSAR-X-Spotlgiht image (17May2010) - Intensity band.

Figure 37 illustrates the Sigma Naught Coefficient of the TerraSAR-X-Spotlgiht image (17May2010) expressed in terms of intensity and decibel (dB).

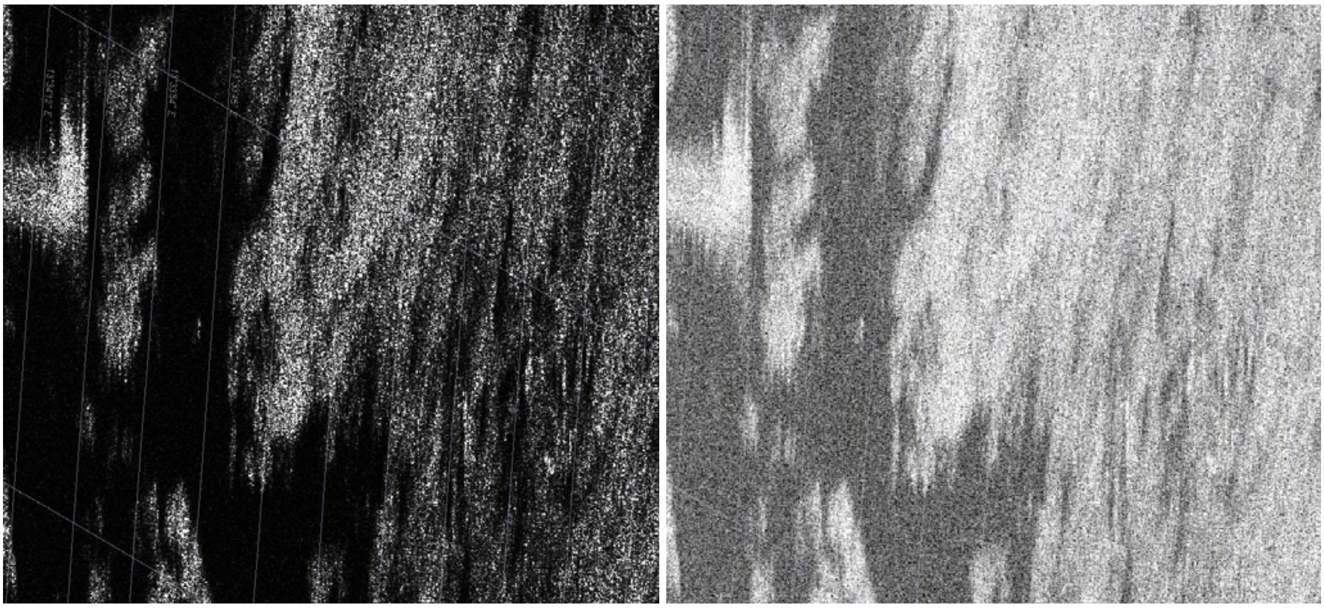


Figure 37 – TerraSAR-X-Spotlgiht image (17May2010) - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 38 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the TerraSAR-X-Spotlgiht image (17May2010) expressed in dB.

Figure 38 – TerraSAR-X-Spotlgiht image (17May2010) - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 39 shows the Sigma Naught (σ°) in dB after some colour manipulation and the histogram of the Sigma Naught (σ°) image.

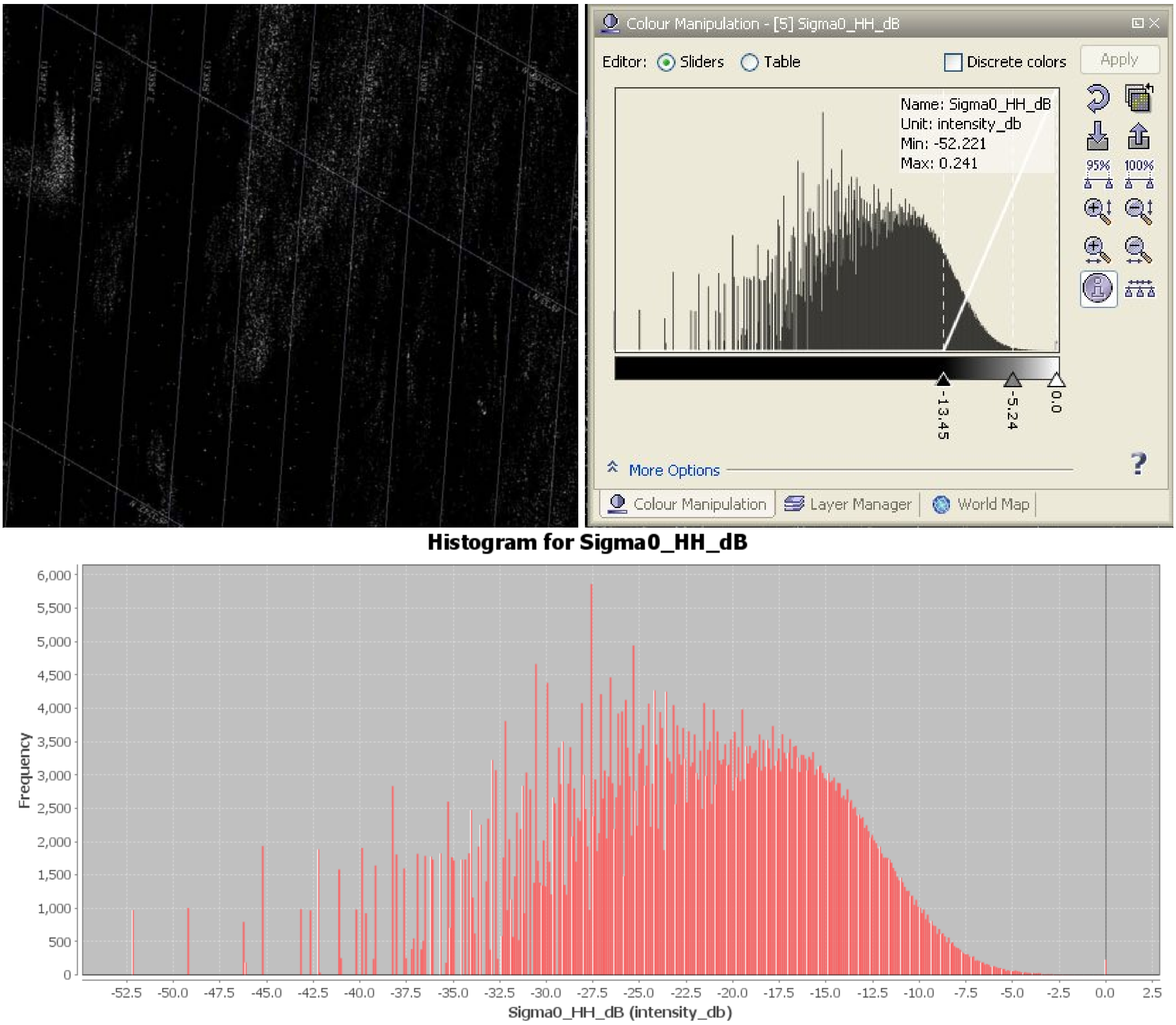


Figure 39 – TerraSAR-X-Spotlgiht image (17May2010) - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 15 gives the statistics of the Sigma Naught (σ°) TerraSAR-X-Spotlgiht image (17May2010). The Sigma Naught (σ°) range from -52.2 dB up to 0.24 dB. The Mean value is -22.4 dB, the Median is -21.9 dB and the standard deviation is 7.6 dB.

Table 15 – Statistics of the TerraSAR-X-Spotlgiht image (17May2010) (05:27 UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	679329	
Number of considered pixels:	679329	
Ratio of considered pixels:	100.0 %	
Minimum:	-52.22117233276367	intensity_db
Maximum:	0.24077458679676056	intensity_db
Mean:	-22.357163888190954	intensity_db
Median:	-21.882598111911275	intensity_db
Std-Dev:	7.615677494513701	intensity_db
Coefficient of Variation:	-0.34063676087509165	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected (Fig. 39), we get values ranging from -11.0 dB up to -0.4 dB. The analysis of the Sigma Naught values (σ°) of the targets and the area around the targets shows a significant contrast.

5.5.2 – Radarsat2-Spotlight, 17May2009(17:10UTC), Portoroz-Slovenia

Figure 40 gives an overview of the Radarsat2-Spotlgiht image (17May2010) and the Intensity band of the selected subset.

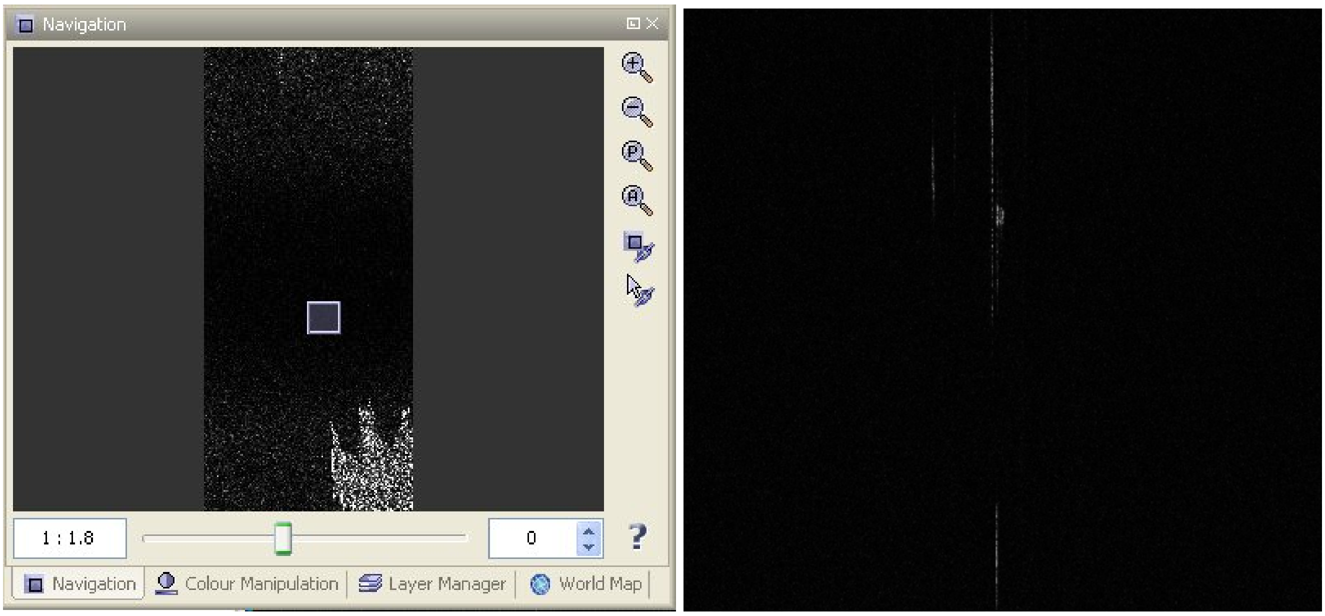


Figure 40 – Radarsat2-Spotlight 17May2010 - On the left, an overview of the SAR image. On the right the Intensity band, of the subset represented by a small square on the left.

Figure 41 illustrates the Sigma Naught Coefficient of the Radarsat2-Spotlgiht image (19Dec.2009) expressed in terms of intensity and decibel (dB).

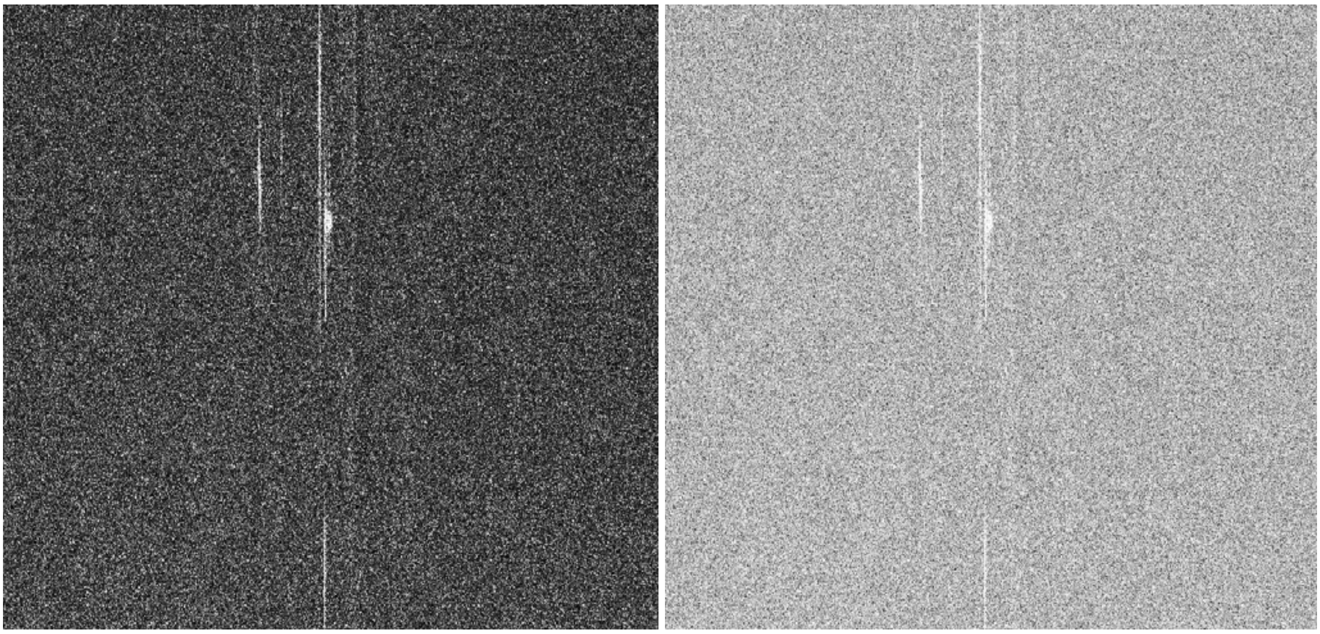


Figure 41 – Radarsat2-Spotlight 17May2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 42 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2-Spotlgiht image (17May2010) expressed in dB.

Figure 42 – Radarsat2-Spotlight 17May2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 43 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

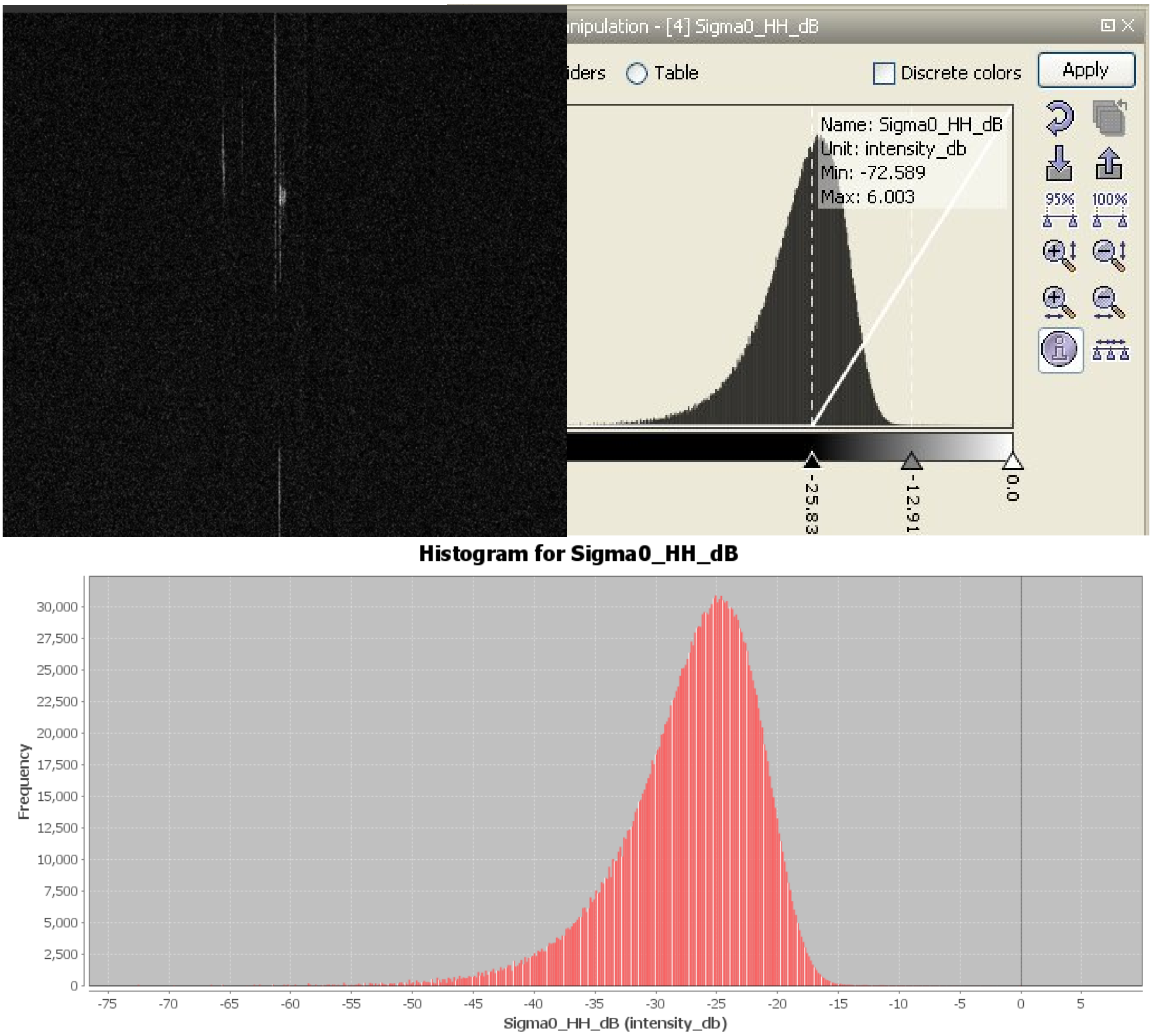


Figure 43 – Radarsat2-Spotlight 17May2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 16 gives the statistics of the Sigma Naught (σ°) Radarsat2-Spotlight image (17May2010). The Sigma Naught (σ°) range from -72.5 dB up to 6.0 dB. The Mean value is -27.1 dB, the Median is -26.25.9 dB and the standard deviation is 5.6 dB.

Table 16– Statistics of the Radarsat2-Spotlight 17May2010 (18:23h)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	2366405	
Number of considered pixels:	2366405	
Ratio of considered pixels:	100.0 %	
Minimum:	-72.58867645263672	intensity_db
Maximum:	6.0027313232421875	intensity_db
Mean:	-27.168289278068105	intensity_db
Median:	-26.25647134400344	intensity_db
Std-Dev:	5.6462391826149005	intensity_db
Coefficient of Variation:	-0.20782456826256285	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 43, we get values ranging from -3.2 dB up to 6.0 dB. The analysis of the Sigma Naught values (σ°) of the targets and the area around the targets shows a significant contrast.

5.5.3 – TerraSAR-X-Spotlight, 18May2010 (5:10AM UTC), Portoroz-Slovenia

Figure 44 gives an overview of the TerraSAR-X-Spotlight image (18May2010) and the Intensity band of the selected subset.

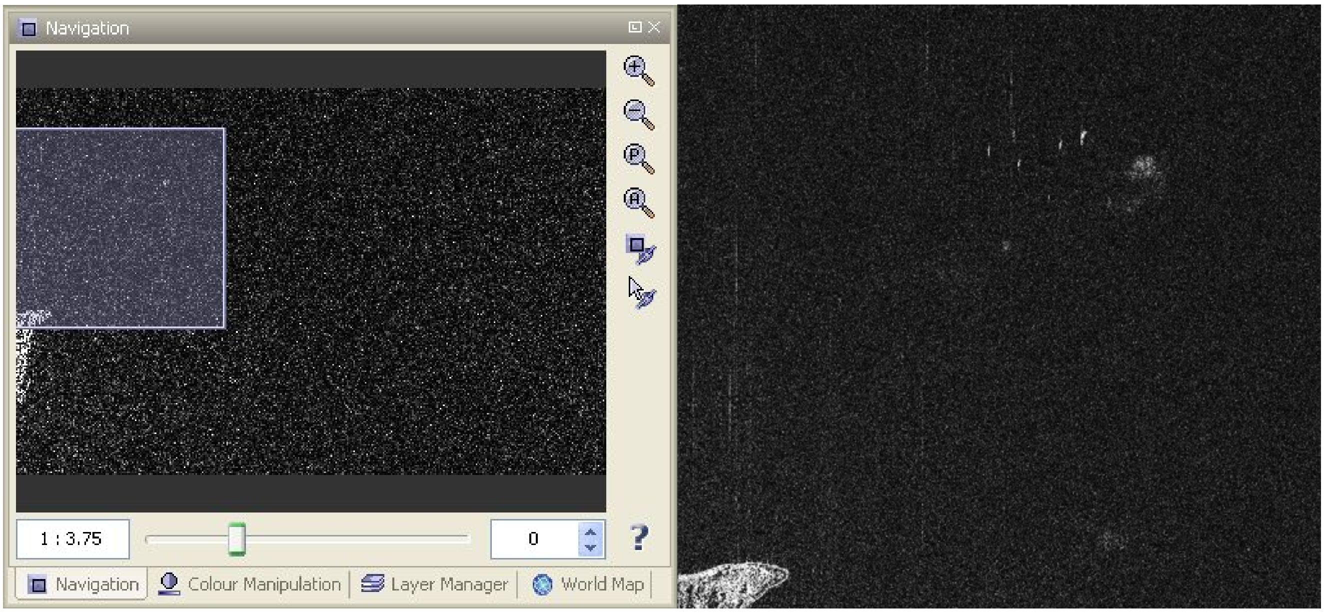


Figure 44 – TerraSAR-X-Spotlight 18May2010 - On the left, an overview of the SAR image. On the right the Intensity band of the subset represented by the small square on the left.

Figure 45 illustrates the Sigma Naught Coefficient of the Radarsat2- Ultrafine image (21Dec.2009) expressed in terms of intensity and decibel (dB).

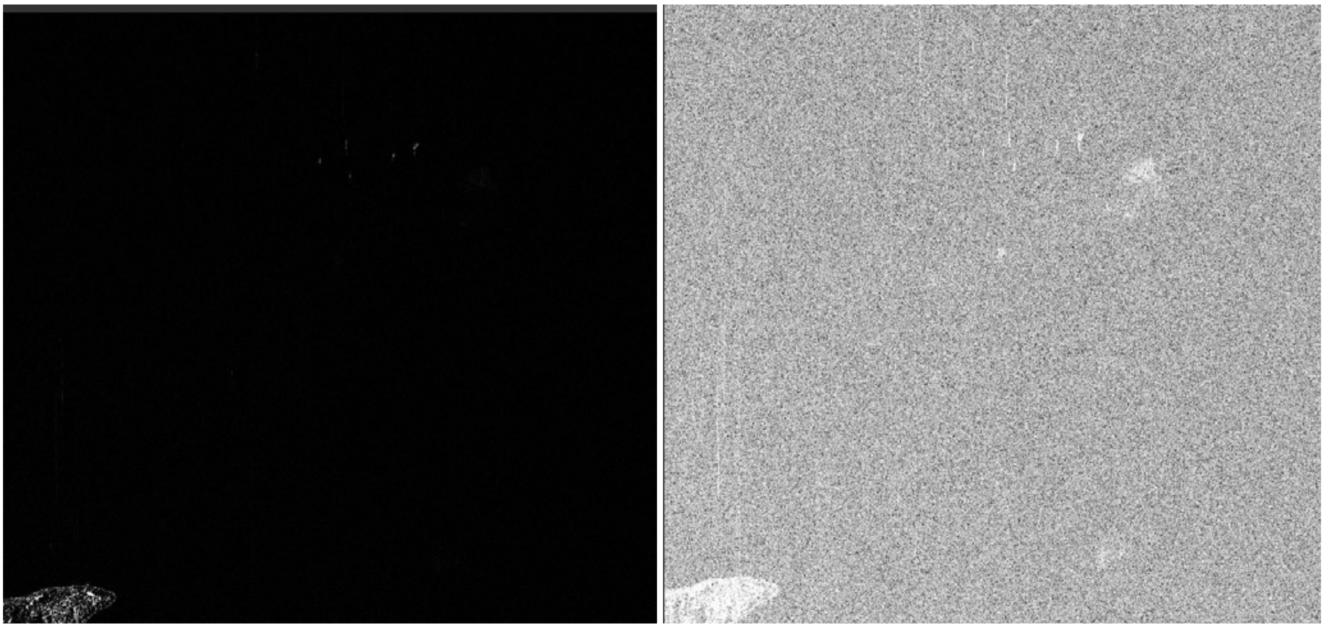


Figure 45 – TerraSAR-X-Spotlight 18May2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 46 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the TerraSAR-X-Spotlight 18May2010 image (21Dec.2009) expressed in dB.

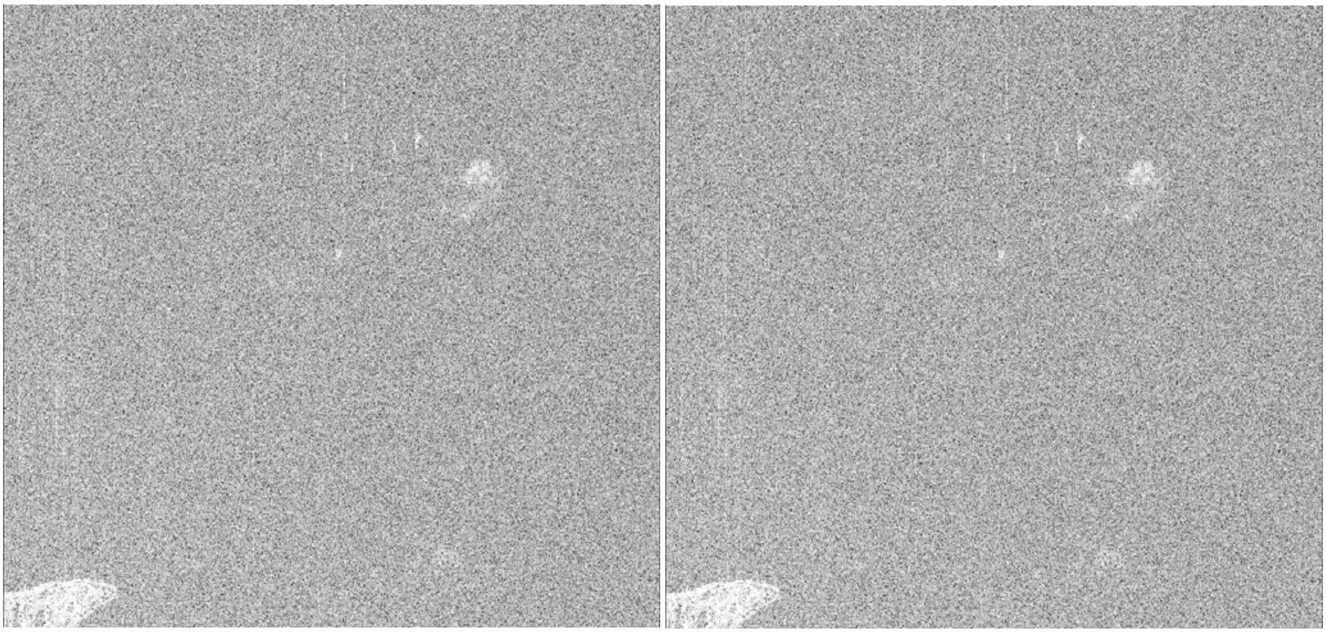


Figure 46 – Radarsat2-Ultrafine 21Dec.2009 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 47 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

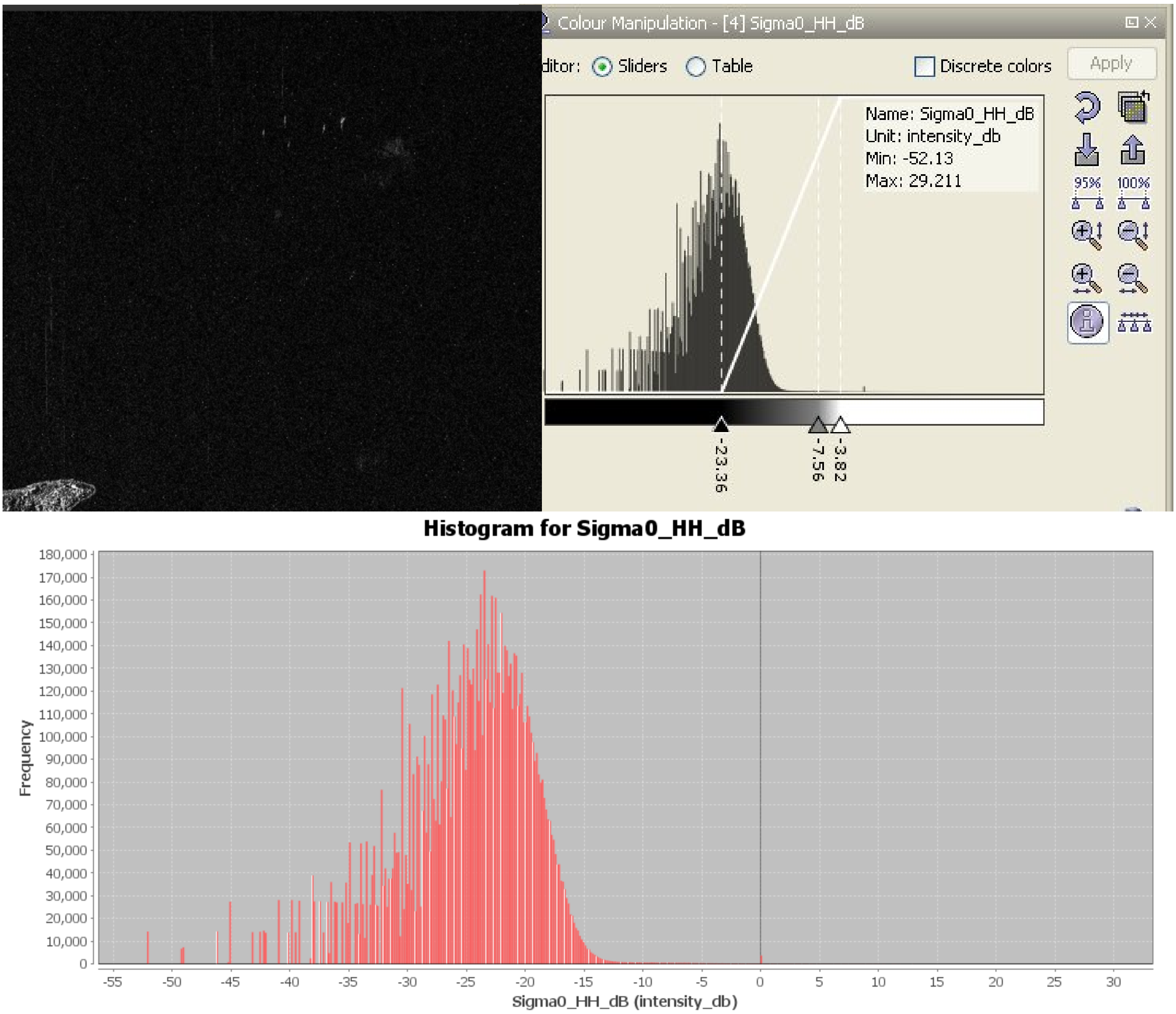


Figure 47 – TerraSAR-X-Spotlight 18May2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 17 gives the statistics of the Sigma Naught (σ°) TerraSAR-X-Spotlight 18May2010. The Sigma Naught (σ°) range from -52.1 dB up to 29.2 dB. The Mean value is -24.8 dB, the Median is -24.1 dB and the standard deviation is 5.7 dB.

Table 17– Statistics of the Radarsat2- Ultrafine image 21Dec.2009 (18:36h)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	10295264	
Number of considered pixels:	10295264	
Ratio of considered pixels:	100.0 %	
Minimum:	-52.129581451416016	intensity_db
Maximum:	29.211238861083984	intensity_db
Mean:	-24.861077864391962	intensity_db
Median:	-24.16867446899414	intensity_db
Std-Dev:	5.711316380685563	intensity_db
Coefficient of Variation:	-0.22972922310535654	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 47, we get values ranging from -6.7 dB up to 6.3 dB. The analysis of the Sigma Naught values (σ°) of the targets and the area around the targets shows a significant contrast.

5.5.4 – TerraSAR-X-Spotlight, 31May2010(16:50 UTC),Portoroz-Slovenia

Figure 48 gives an overview of the TerraSAR-X-Spotlight image (31May2010) and the Intensity band of the selected subset.

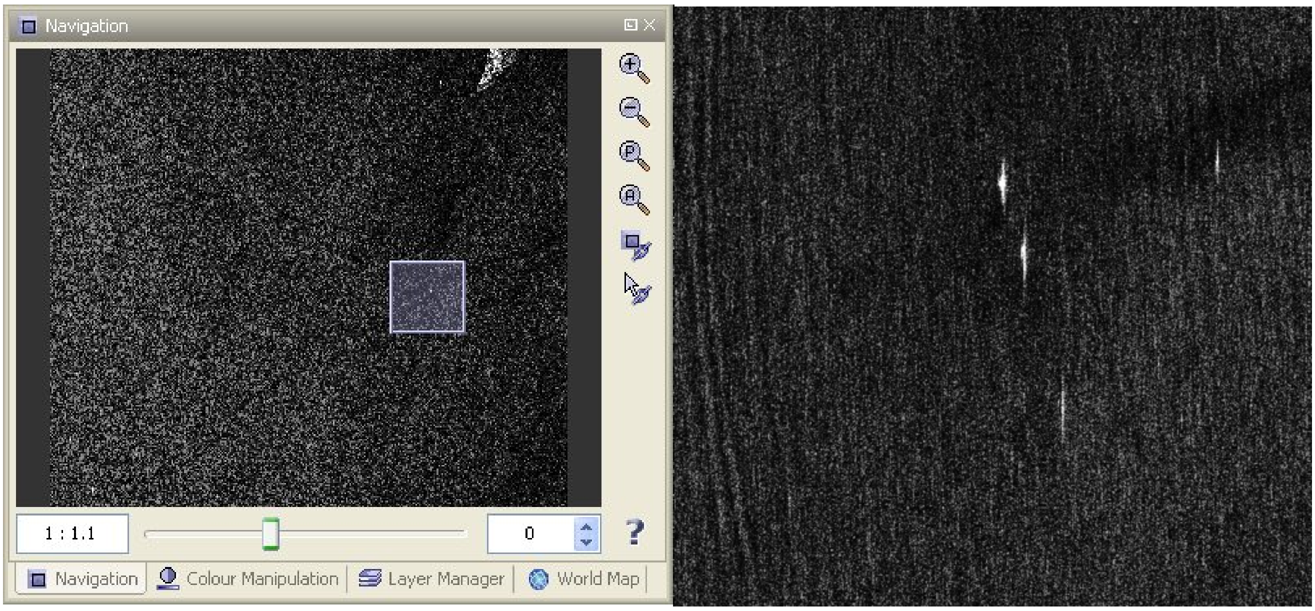


Figure 48 – TerraSAR-X-Spotlight 31May2010 - On the left, an overview of the SAR image. On the right the Intensity band of the subset represented by the small square on the left.

Figure 49 illustrates the Sigma Naught Coefficient of the TerraSAR-X-Spotlight 31May2010 expressed in terms of intensity and decibel (dB).

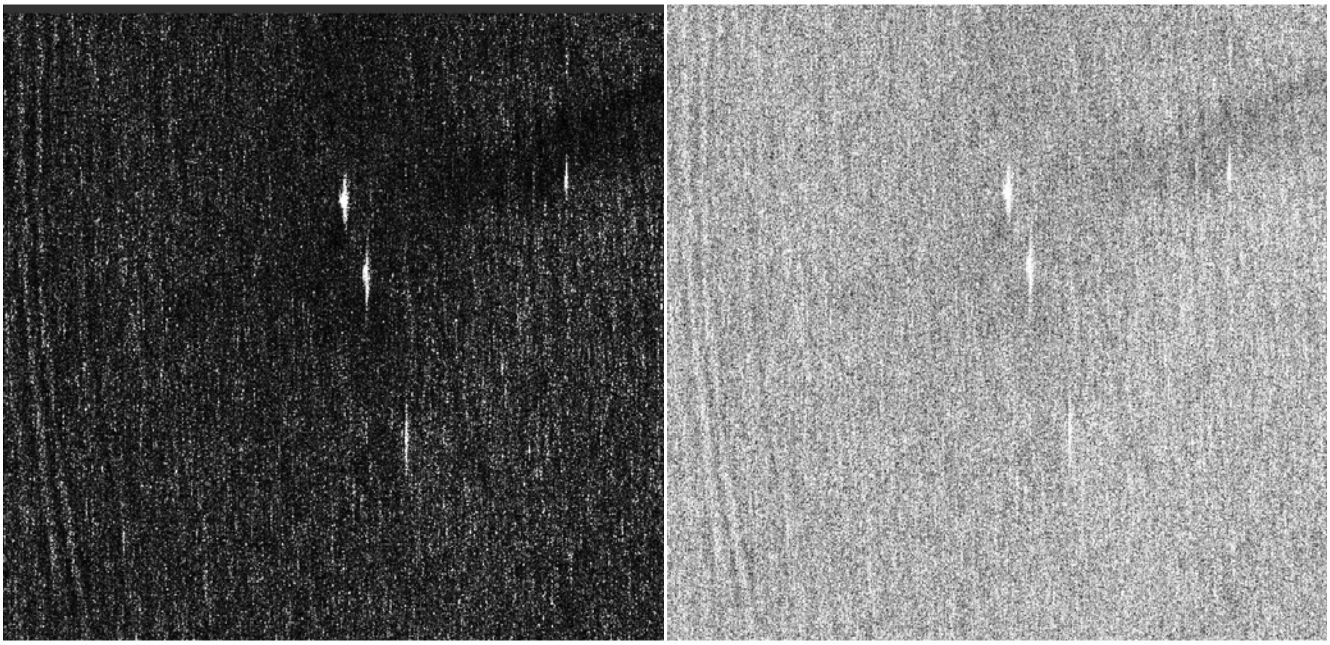


Figure 49 – TerraSAR-Spotlight 31May2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 50 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the TerraSAR-Spotlight image (31May2010) expressed in dB.

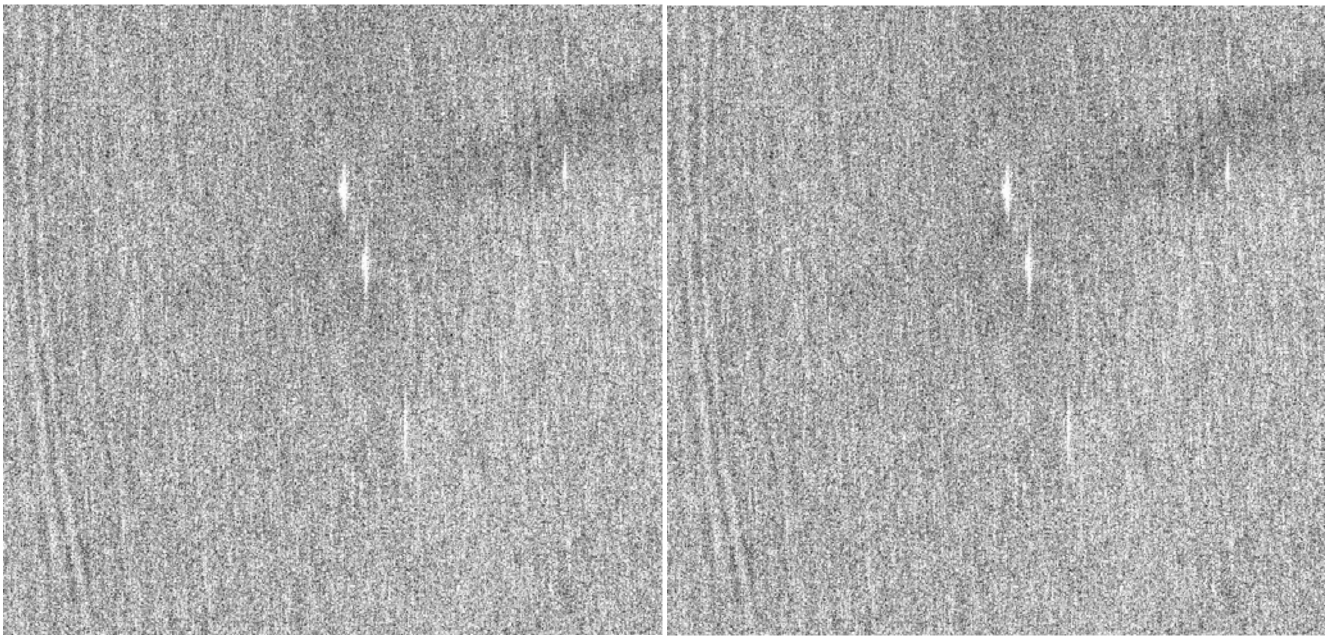


Figure 50– TerraSAR-X-Spotlight 31May.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 51 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

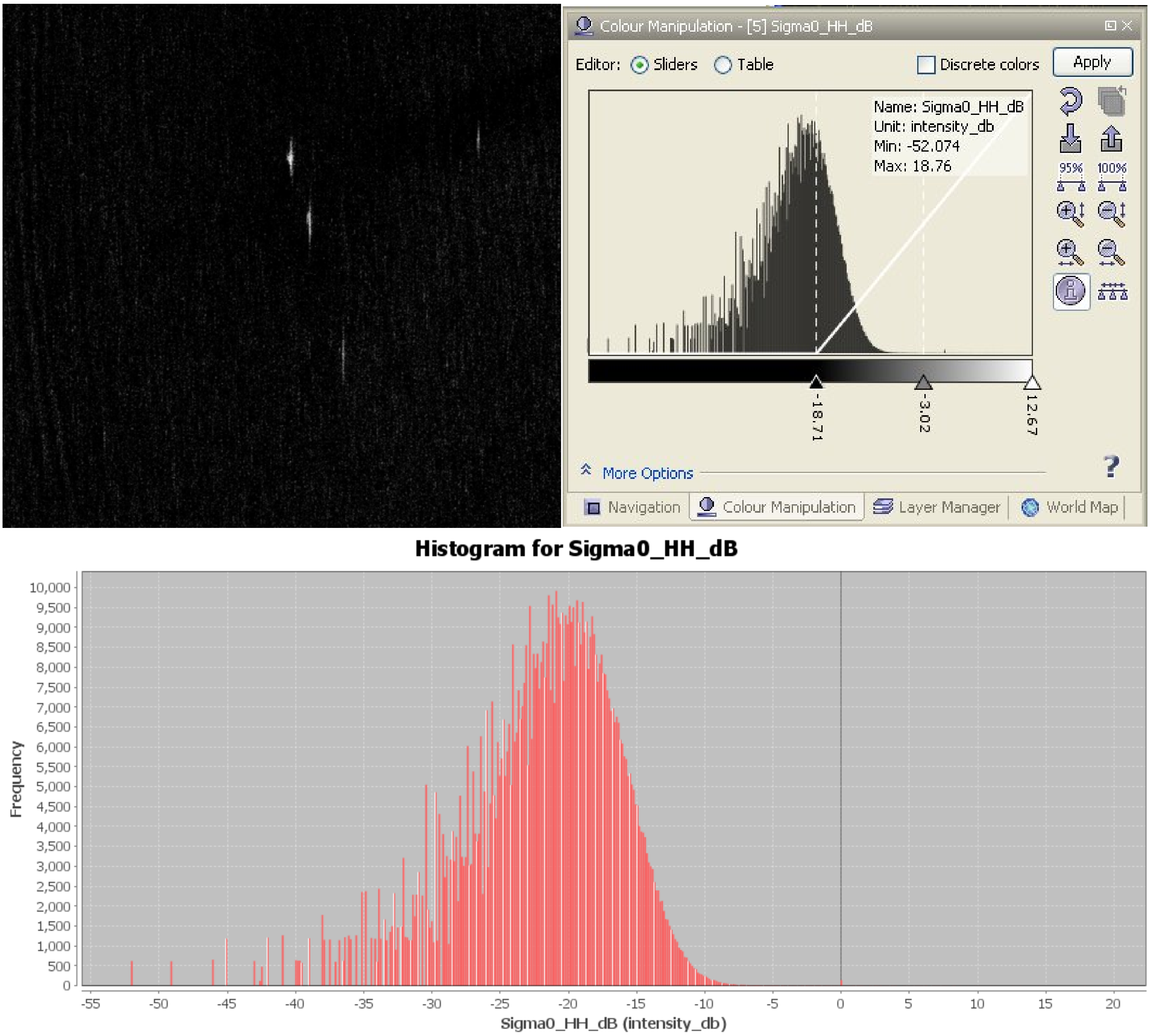


Figure 51 – TerraSAR-X-Spotlight 31May2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 18 gives the statistics of the Sigma Naught (σ°) TerraSAR-X-Spotlight 31May2010. The Sigma Naught (σ°) range from -52.0 dB up to 18.7 dB. The Mean value is -21.9 dB, the Median is 21.2 dB and the standard deviation is 5.8 dB.

Table 18– Statistics of the TerraSAR-X- Spotlight image 31May2010.

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	826434	
Number of considered pixels:	826434	
Ratio of considered pixels:	100.0 %	
Minimum:	-52.07429122924805	intensity_db
Maximum:	18.75992774963379	intensity_db
Mean:	-21.953085378863303	intensity_db
Median:	21.222668509930372	intensity_db
Std-Dev:	5.803330268265516	intensity_db
Coefficient of Variation:	-0.2643513044775004	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 51, we get values ranging from -2.9 dB up to 21.5 dB. The analysis of the Sigma Naught values (σ°) of the targets and the area around the targets shows a significant contrast.

5.5.5 – Radarsat2-Spotlight, 31May2010, Portoroz-Slovenia

Figure 52 gives an overview of the Radarsat2-Spotlight image (31May2010) and the Intensity band of the selected subset.

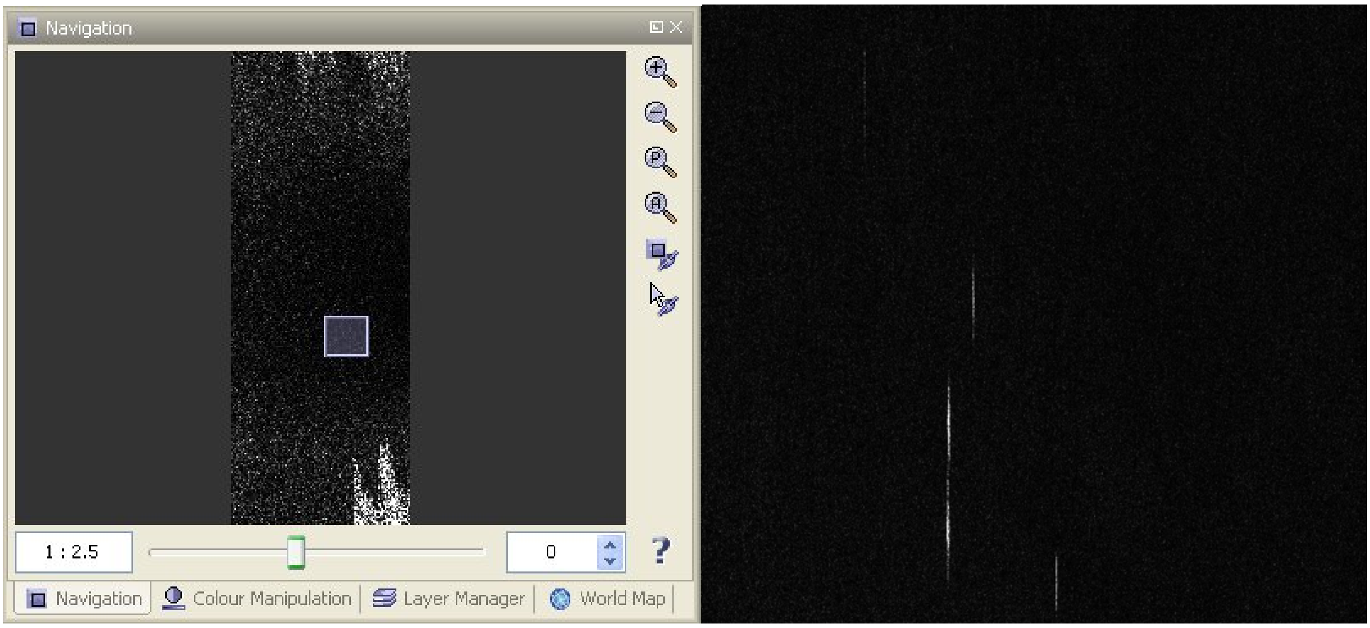


Figure 52 – Radarsat2-Spotlight, 31May2010 - On the left, an overview of the SAR image. On the right the Intensity band of the subset represented by the small square on the left.

Figure 53 illustrates the Sigma Naught Coefficient of the Radarsat2-Spotlight image (31May2010) expressed in terms of intensity and decibel (dB).

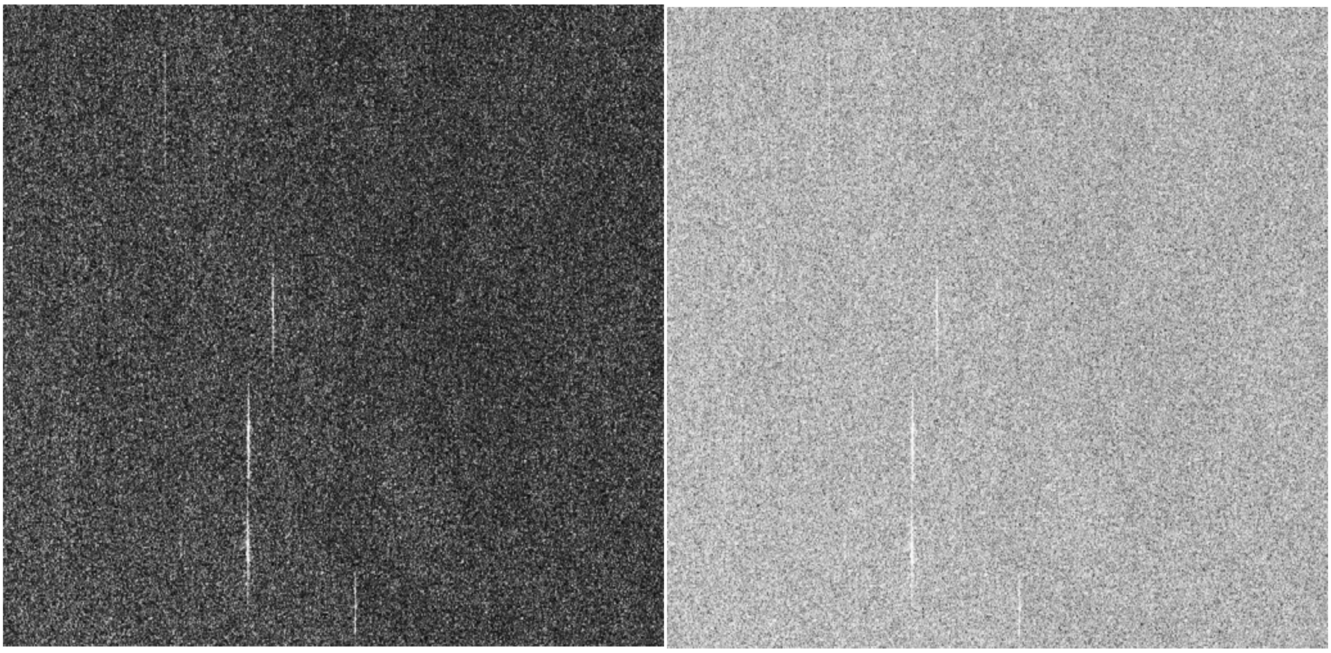


Figure 53 – Radarsat2-Spotlight, 31May2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 54 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2-Spotlight (31May2010) expressed in dB.

Figure 54 – Radarsat2-Spotlight, 31May2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 55 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

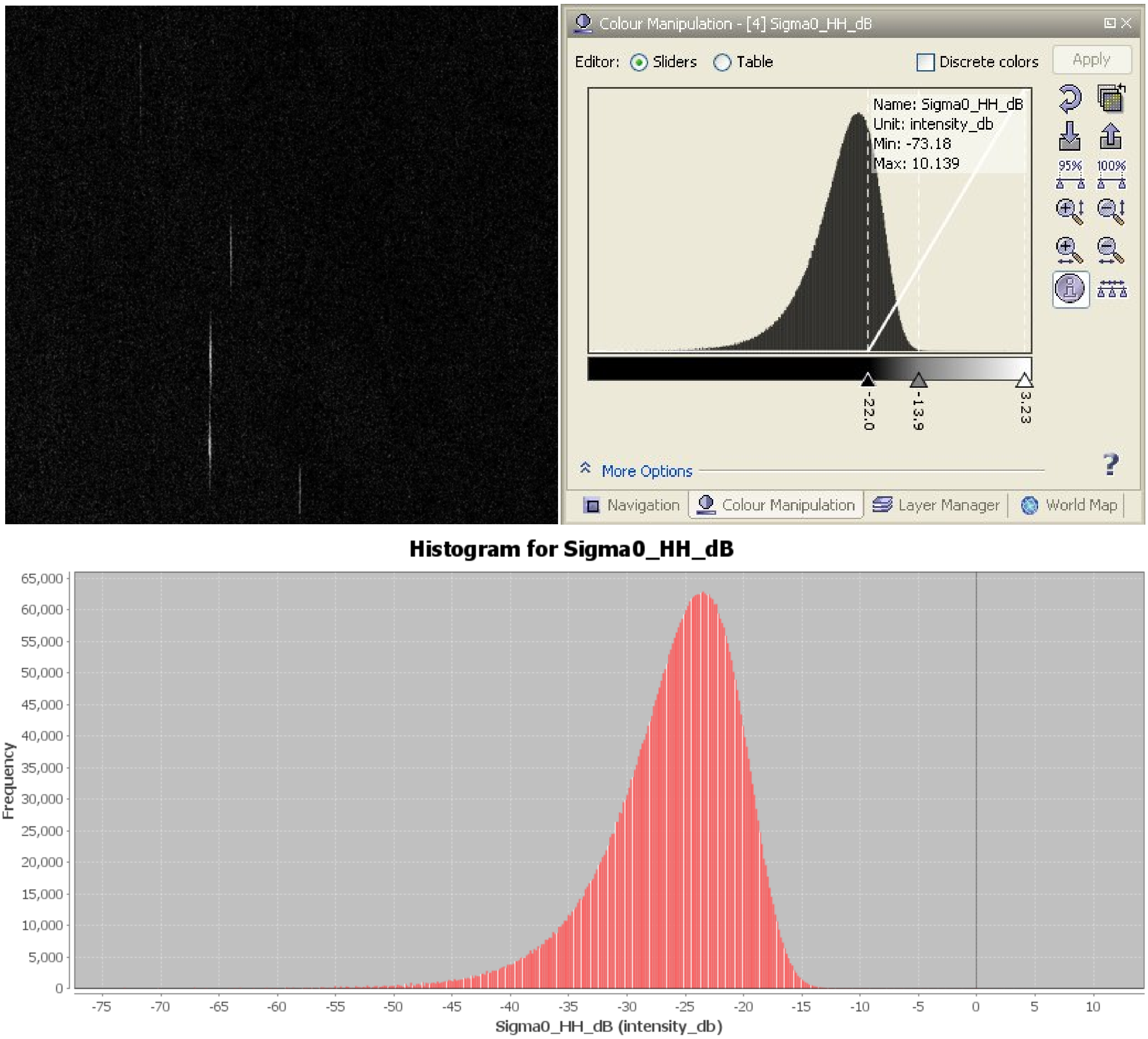


Figure 55 – Radarsat2-Spotlight, 31May2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 19 gives the statistics of the Sigma Naught (σ°) Radarsat2-Spotlight image (31May2010). The Sigma Naught (σ°) range from -73.1 dB up to 10.1 dB. The Mean value is -25.9 dB, the Median is -25.1 dB and the standard deviation is 5.6 dB.

Table 19– Statistics of the TerraSAR-X-Stripmap image 22Dec.2009 (18:31h)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	4609808	
Number of considered pixels:	4609808	
Ratio of considered pixels:	100.0 %	
Minimum:	-73.18006134033203	intensity_db
Maximum:	10.138691902160645	intensity_db
Mean:	-25.97146591604214	intensity_db
Median:	-25.174139061942697	intensity_db
Std-Dev:	5.649486746749415	intensity_db
Coefficient of Variation:	-0.21752665607253024	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 55, we get values ranging from -5.4 dB up to 10.1 dB. The analysis of the Sigma Naught values (σ°) of the targets and the area around the targets shows a significant contrast.

5.5.6 – Radarsat2-Ultrafine,01 June 2010(05:13UTC), Portoroz-Slovenia

Figure 56 gives an overview of the Radarsat2-Ultrafine image (01Jun. 2010) and the Intensity band of the selected subset.

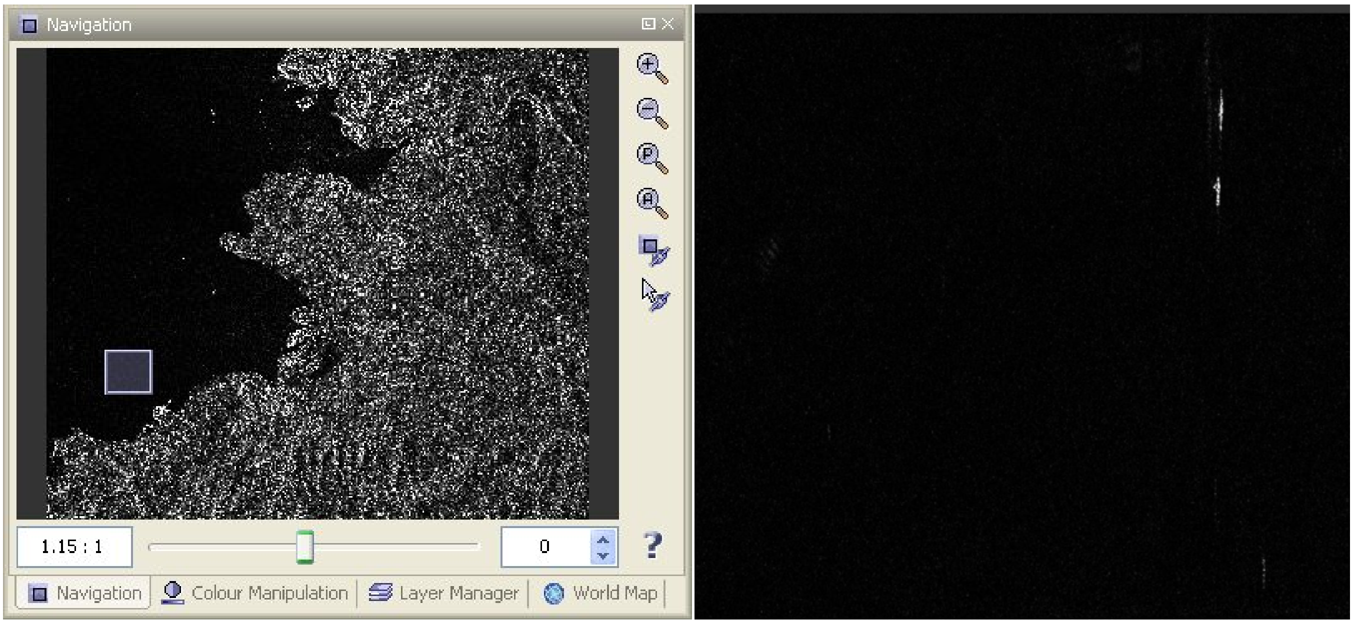


Figure 56 – Radarsat2-Ultrafine, 01Jun.2010 - On the left, an overview of the SAR image. On the right the Intensity band of the subset represented by the small square on the left.

Figure 57 illustrates the Sigma Naught Coefficient of the Radarsat2-Ultrafine image (01Jun.2010) expressed in terms of intensity and decibel (dB).

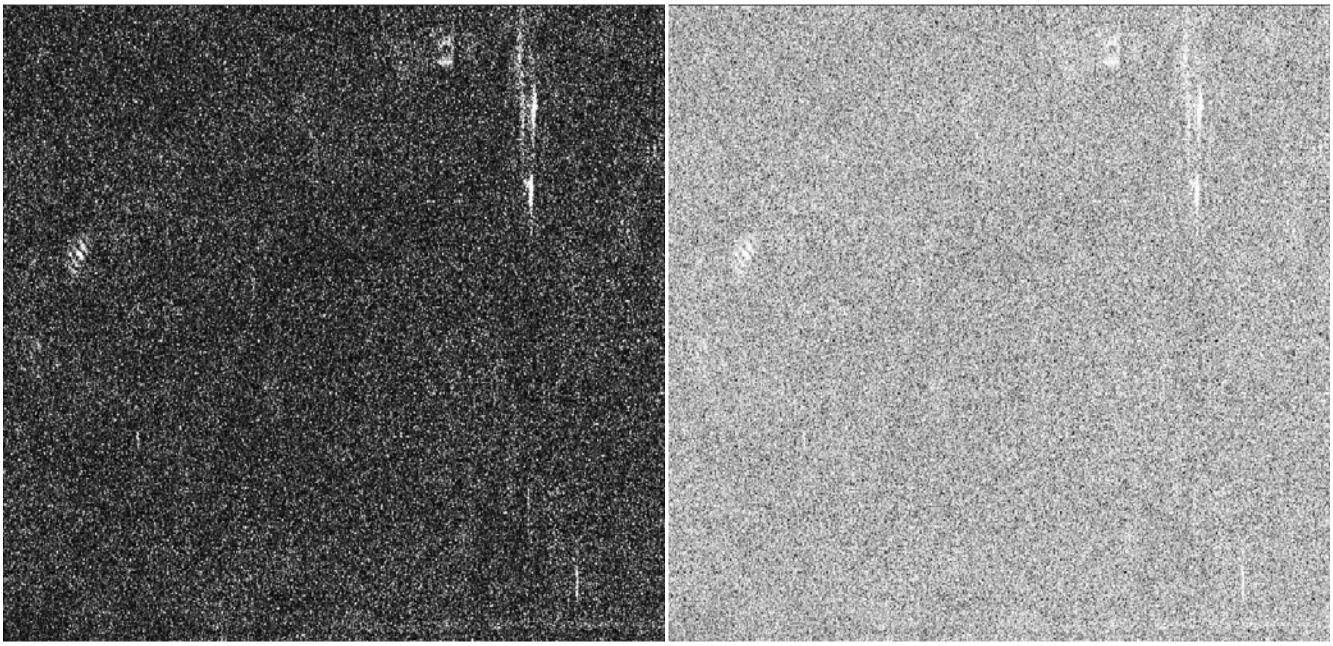


Figure 57 – Radarsat2-Ultrafine, 31May2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 58 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2-Ultrafine image (01Jun.2010) expressed in dB.

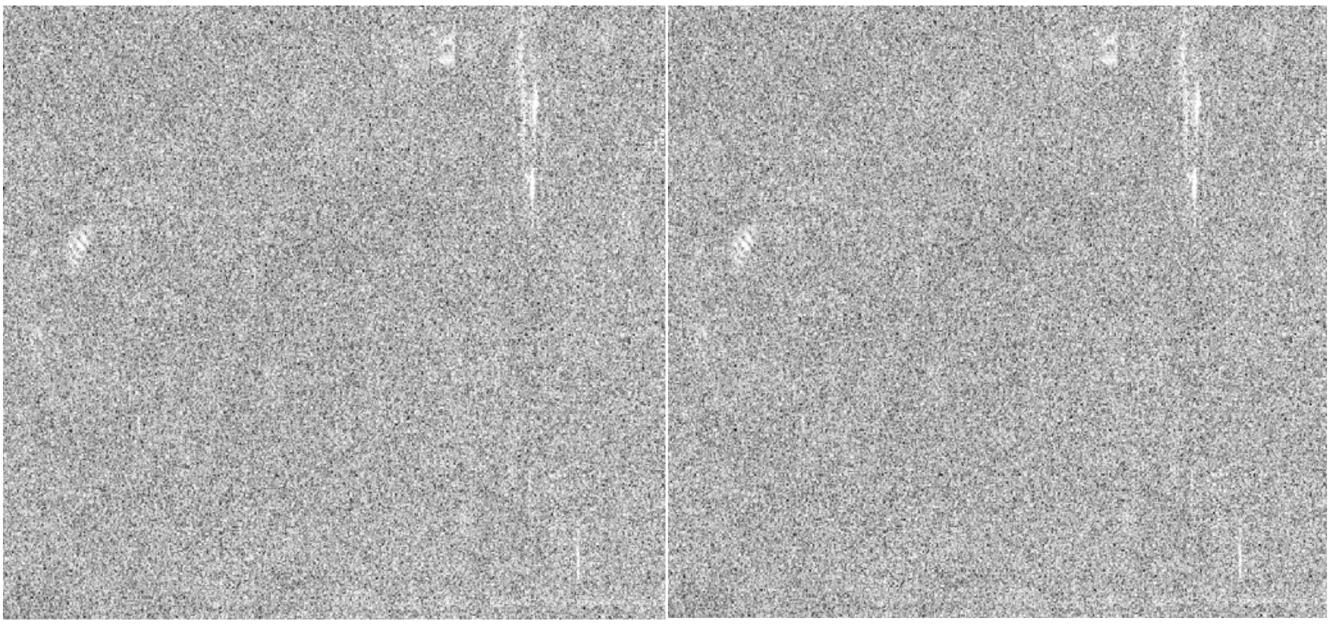


Figure 58 – Radarsat2-Ultrafine, 01Jun.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 59 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

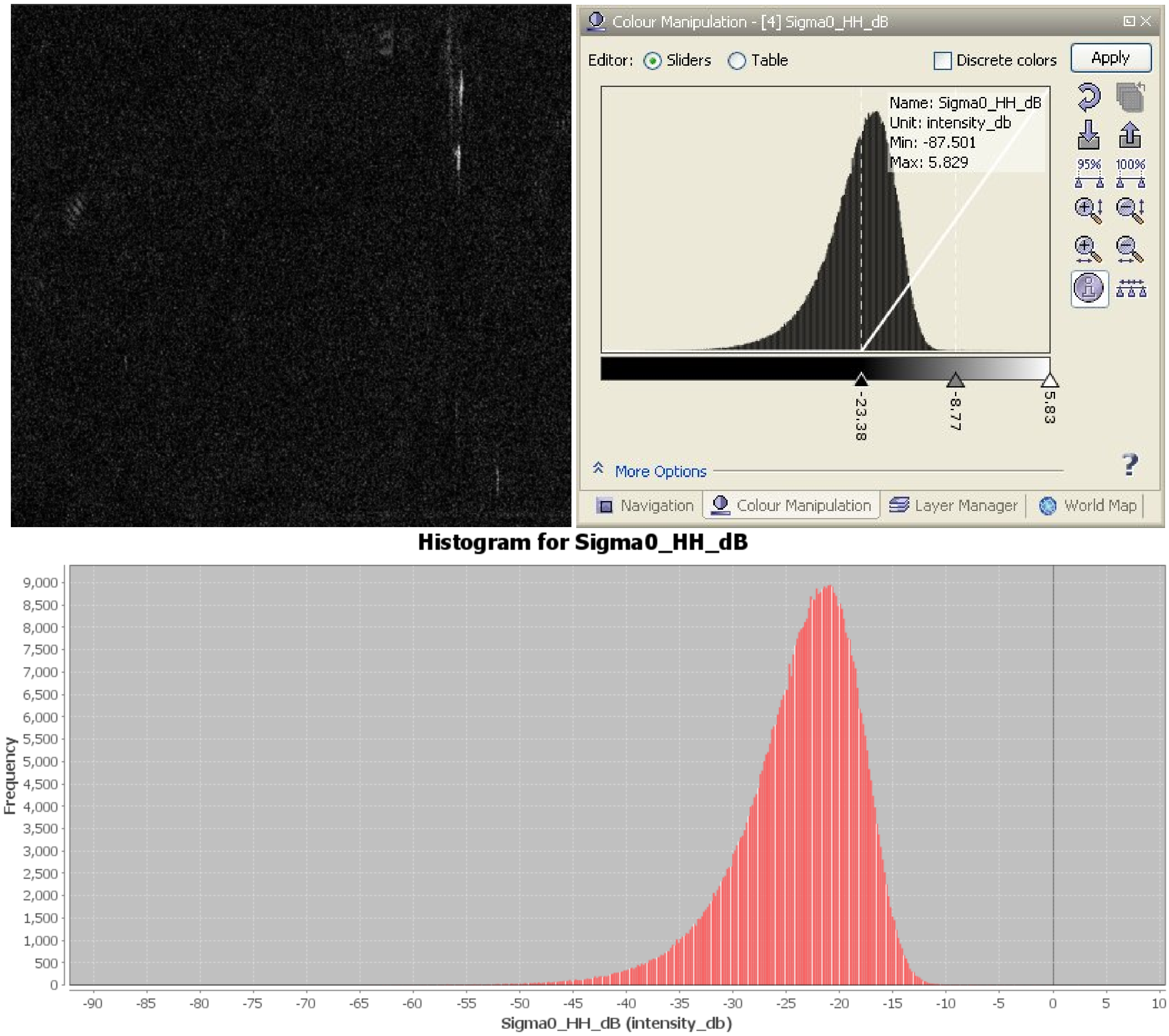


Figure 59 – Radarsat2-Ultrafine, 01Jun.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 20 gives the statistics of the Sigma Naught (σ°) Radarsat2-Spotlight image (31May2010). The Sigma Naught (σ°) range from -87.5 dB up to 5.8 dB. The Mean value is -23.7 dB, the Median is -22.9 dB and the standard deviation is 5.6 dB.

Table 20– Statistics of the Radarsat2-Ultrafine, 01Jun.2010 (05:13UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	581640	
Number of considered pixels:	581640	
Ratio of considered pixels:	100.0 %	
Minimum:	-87.50135803222656	intensity_db
Maximum:	5.829427719116211	intensity_db
Mean:	-23.758723210012796	intensity_db
Median:	-22.971869446337223	intensity_db
Std-Dev:	5.623660288963465	intensity_db
Coefficient of Variation:	-0.23669855509275542	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 59, we get values ranging from -8.4 dB up to 5.8 dB. The analysis of the Sigma Naught values (σ°) of the targets and the area around the targets shows a significant contrast.

5.5.7 – Radarsat2-Spotlight,04 June 2010(05:25UTC), Portoroz-Slovenia

Figure 60 gives an overview of the Radarsat2-Spotlight image (04Jun. 2010) and the Intensity band of the selected subset.

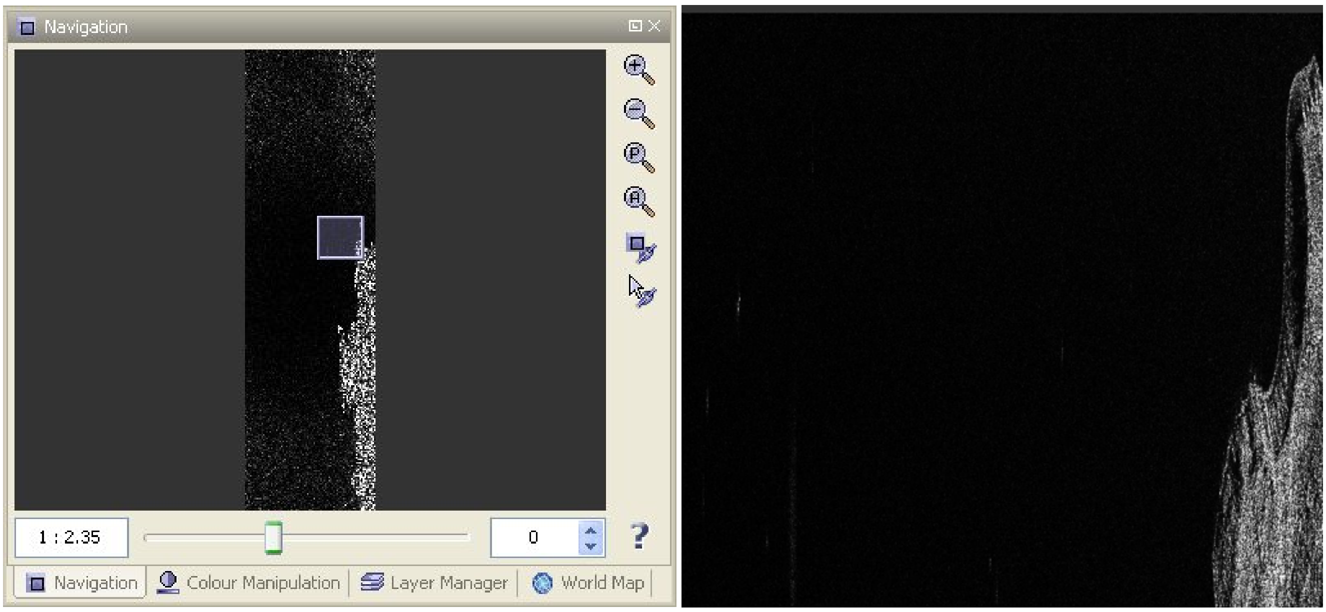


Figure 60 – Radarsat2-Ultrafine, 01Jun.2010 - On the left, an overview of the SAR image. On the right the Intensity band of the subset represented by the small square on the left.

Figure 61 illustrates the Sigma Naught Coefficient of the Radarsat2-Spotlight image (04Jun.2010) expressed in terms of intensity and decibel (dB).

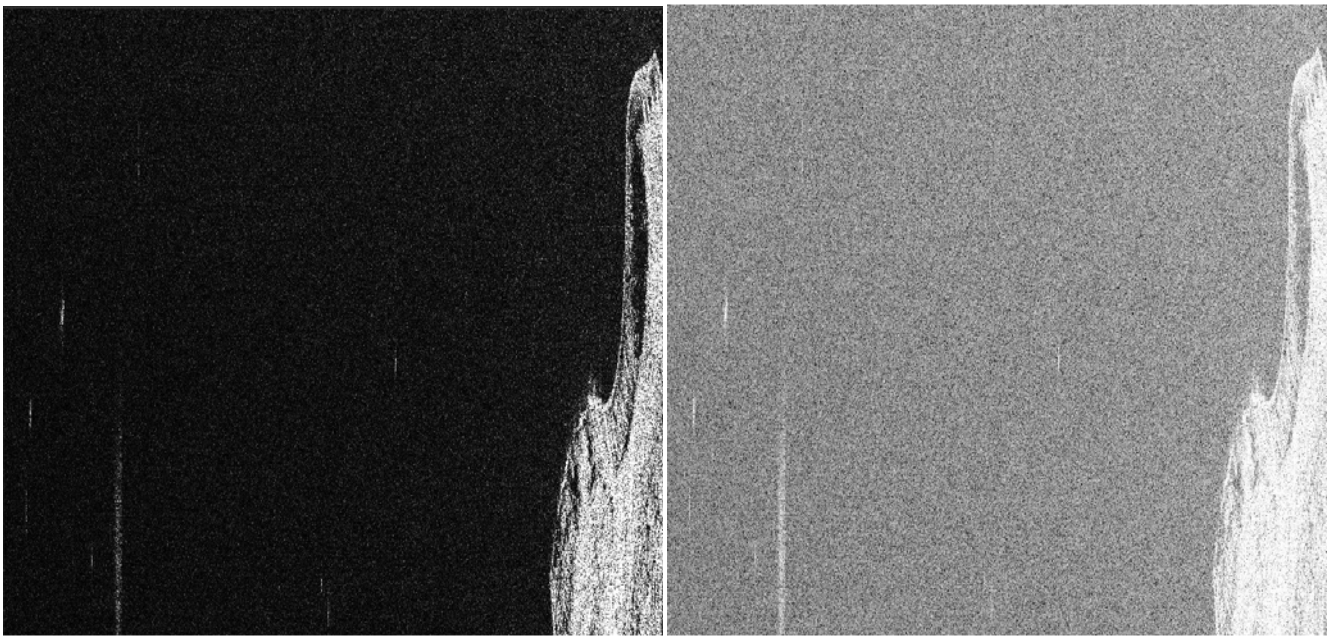


Figure 61 – Radarsat2-Spotlight, 04Jun.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 62 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2-Spotlight image (04Jun.2010) expressed in dB.

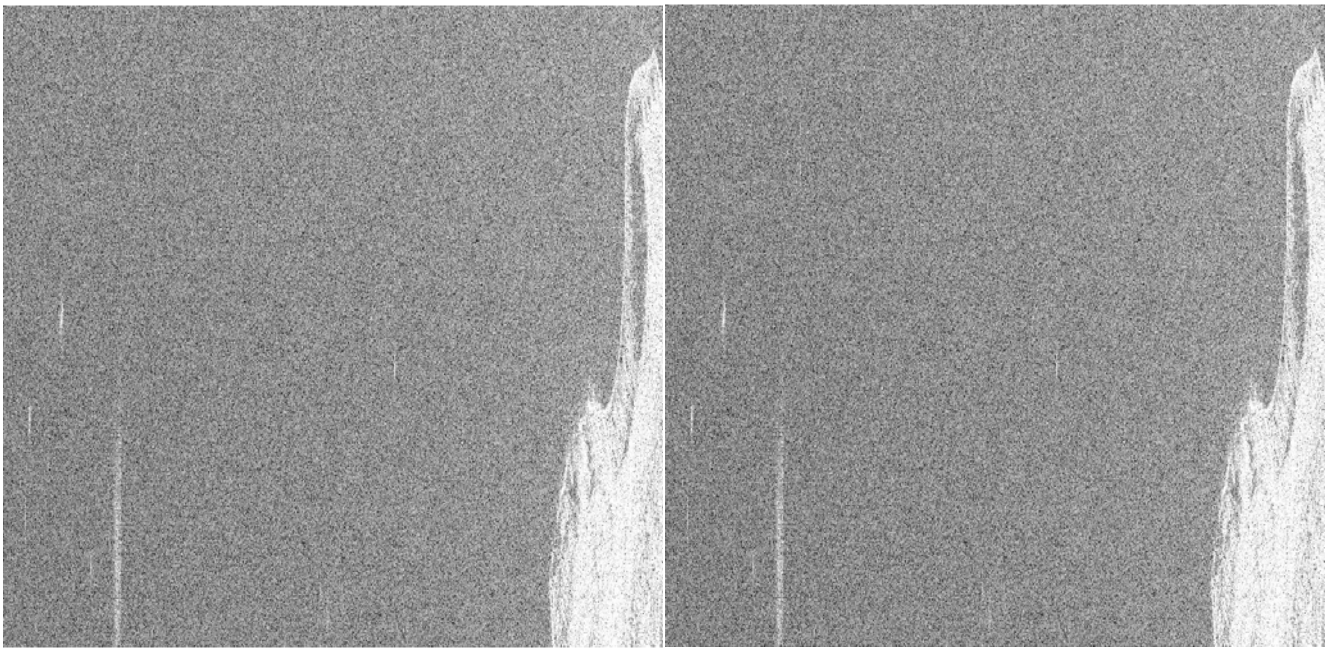


Figure 62 – Radarsat2-Ultrafine, 04Jun.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 63 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

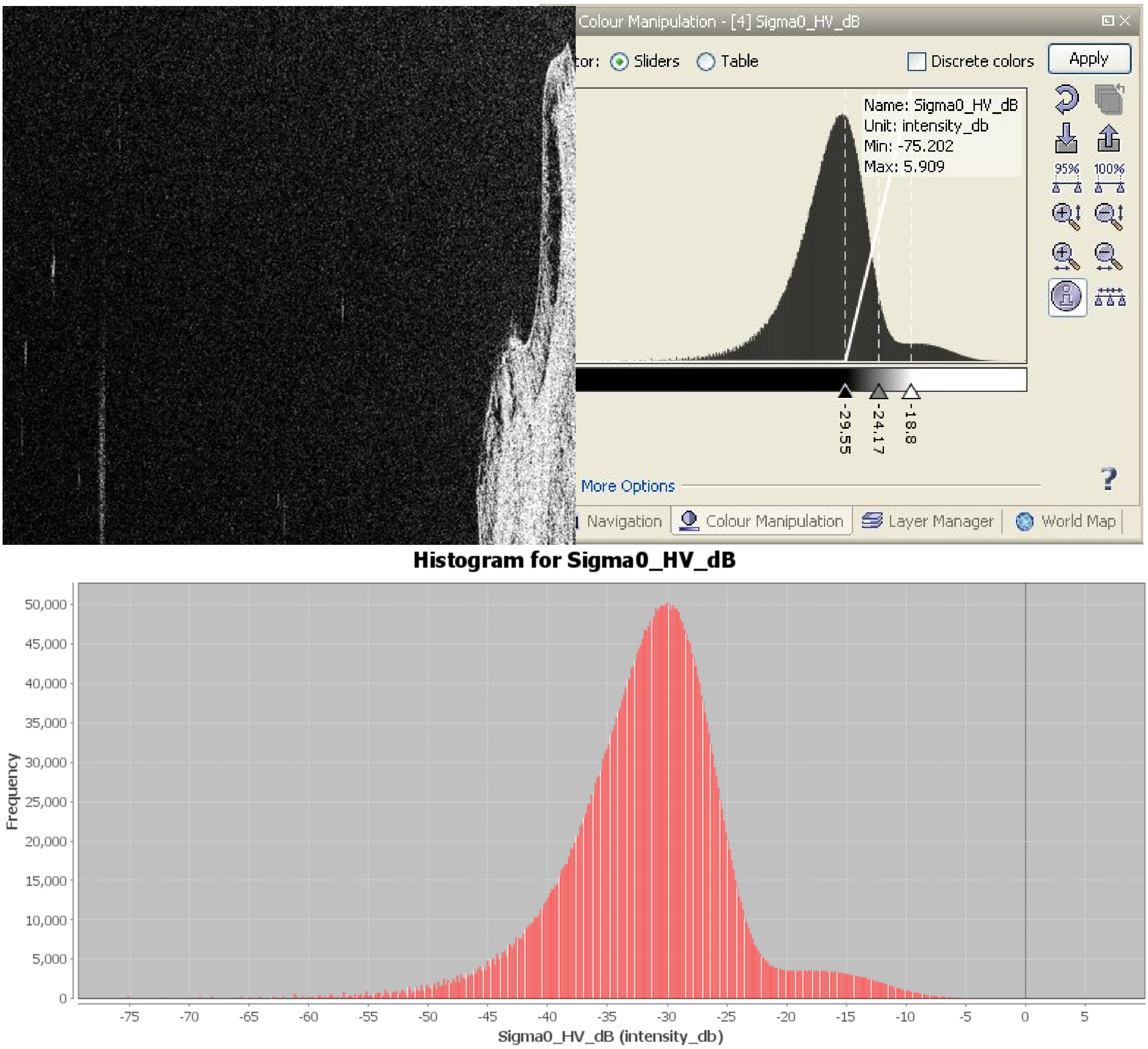


Figure 63 – Radarsat2-Spotlight, 04Jun.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 21 gives the statistics of the Sigma Naught (σ°) Radarsat2-Spotlight image (31May2010). The Sigma Naught (σ°) range from -75.2 dB up to 5.9 dB. The Mean value is -31.4 dB, the Median is -31.1 dB and the standard deviation is 6.7 dB.

Table 21– Statistics of the Radarsat2-Spotlight, 04Jun.2010 (05:25UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	4092855	
Number of considered pixels:	4092855	
Ratio of considered pixels:	100.0 %	
Minimum:	-75.20214080810547	intensity_db
Maximum:	5.909428119659424	intensity_db
Mean:	-31.46020628796632	intensity_db
Median:	-31.10957427628187	intensity_db
Std-Dev:	6.7566168013620596	intensity_db
Coefficient of Variation:	-0.2147670588724029	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 63, we get values ranging from -16.9 dB up to -9.3 dB. The analysis of the Sigma Naught values (σ°) of the targets and the area around the targets shows a significant contrast.

5.6 – Summary of the Preliminary Analysis of the Spaceborne SAR Images

This experiment involved 7 spaceborne SAR images, namely 3 Radarsat2-Spotlight, 1 Radarsat2-Ultrafine and 3 TerraSAR-X-Spotlight. The boats deployed as targets were detected in all the images. Table 22 summarises the characteristics of the SAR images acquired and the targets detected.

Table 22 – List of SAR Satellite Images acquired during the experiment and detected boats.

Date / Time	Place	Satellite / Mode	Ground Truth Data	Detected Boats
SLOVENIA (Portoroz - Piran)				
17.May.2010 (AM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	GPS/Photos/Movies	1 out of 6 + Buoy
17.May.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	" "	5 out of 5 + Buoy
18.May.2010 (AM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	" "	6 out of 6 + Buoy
31.May.2010 (PM)	Portoroz- Slovenia	TerraSAR-X / Spotlight	GPS/Photos	4 out of 4 + Buoy
31.May.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	" "	4 out of 4 + Buoy
01.Jun.2010 (AM)	Portoroz- Slovenia	Radarsat-2 / Ultrafine	" "	3 out of 3
04.Jun.2010 (PM)	Portoroz- Slovenia	Radarsat-2 / Spotlight	" "	4 out of 4 + Buoy

Table 23 gives the minimum and maximum Sigma Naught (σ°) of the targets detected in each SAR image.

Table 23 – Minimum and maximum Sigma Naught (σ°) of the targets detected in each SAR image.

Date /Time UTC (LT)/Pass	Satellite / Image Mode / Polarisation	Sigma Naught (σ°) Min / Max
17.May.2010 / 5:27AM UTC (7:27AM LT) / DES	TerraSAR-X / Spotlight / HH	-11.0dB / -0.4dB
17.May.2010 / 17:10 UTC-(15:27AM LT) / ASC	Radarsat2 / Spotlight / HH	-3.2dB / 6.0dB.
18.May.2010 / 5:10AM UTC-(7:10AM LT) / DES	TerraSAR-X / Spotlight / HH	-6.7dB / 6.3dB
31.May.2010 / 16:50 UTC-(14:50AM LT) / ASC	TerraSAR-X / Spotlight / HH	-2.9dB / 21.5 dB
31.May.2010 / 17:02 UTC-(15:02AM LT) / ASC	Radarsat2 / Spotlight / HH	-5.4dB / 10.1dB
01.June.2010 / 05:13 UTC-(07:13AM LT) / DES	Radarsat2 / Ultrafine / HH	-8.4dB / 5.8dB
04.June.2010 / 05:25 UTC-(07:13AM LT) / ASC	Radarsat2 / Spotlight / HH	-16.9dB / -9.3dB

6. – Preliminary Conclusions

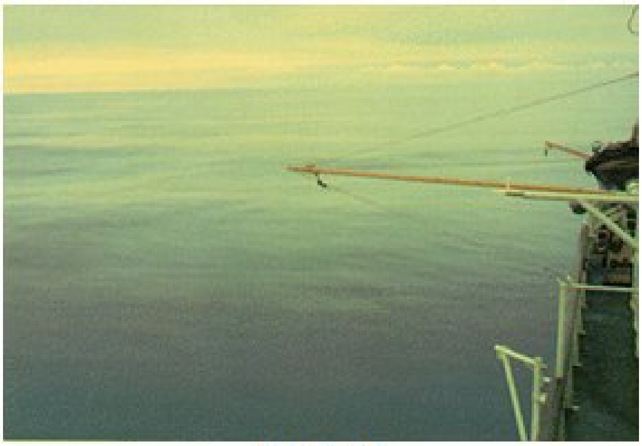
The relatively reduced amount of data collected and analysed does not allow drawing final conclusions about the feasibility of using SAR Satellites for small boat detection. In this experiment 7 spaceborne SAR images were used, namely:

Date: 17.May.2010 **Time:** 5:27AM UTC- (7:27AM LT) / **Pass:** Descending	**Satellite/Mode:** TerraSAR-X / Spotlight **Polarisation** HH
Date: 17.May.2010 **Time:** 17:10 UTC-(15:27AM LT) / **Pass:** Ascending	**Satellite/Mode:** Radarsat2 / Spotlight **Polarisation** HH
Date: 18.May.2010 **Time:** 5:10AM UTC-(7:10AM LT) / **Pass:** Descending	**Satellite/Mode:** TerraSAR-X / Spotlight **Polarisation** HH
Date: 31.May.2010 **Time:** 16:50 UTC-(14:50AM LT) / **Pass:** Ascending	**Satellite/Mode:** TerraSAR-X / Spotlight **Polarisation** HH
Date: 31.May.2010 **Time:** 17:02 UTC-(15:02AM LT) / **Pass:** Ascending	**Satellite/Mode:** Radarsat2 / Spotlight **Polarisation** HH
Date: 01.June.2010 **Time:** 05:13 UTC-(07:13AM LT) / **Pass:** Descending	**Satellite/Mode:** Radarsat2 / Spotlight **Polarisation** HH
Date: 04.June.2010 **Time:** 05:25 UTC-(07:13AM LT) / **Pass:** Ascending	**Satellite/Mode:** Radarsat2 / Spotlight **Polarisation** HH

The analyses of the 7 spaceborne SAR images showed that the vast majority of the small boats deployed as targets were detected. All the boats with sizes ranging from 6m up to 37 were detected in 6 of the 7 spaceborne SAR images acquired. Only in the first spaceborne SAR image acquired on 17May2010 by 5:27 UTC the SAR signatures could not be isolated by visual analysis from the sea clutter background. Apparently this was due to the relatively low incidence angle (about 20°), which is the lower limit of the full performance range of incidence angles and to the sea state. In the remaining 6 SAR images the relatively calm sea state and good weather conditions observed during the campaign played an important role in the detections. The results are encouraging because several boats with different characteristics (e.g. size, shape, materials, etc.) were used and successfully detected in different types and modes of spaceborne SAR images, including Radarsat2-Spotlight and Ultrafine and TerraSAR-X-Spotlight.

6.1 – Small Boat Detection in SAR Satellite Imagery

The Small Boat detection campaigns conducted by the EC-JRC thus far using TerraSAR-X and Radarsat2 spaceborne SAR images show that it is possible to the detect Small Boats in spaceborne SAR images under suitable sea state and wind force associated parameters (e.g. wind speed, wave period, wave height, etc.). The results indicate that it seems to be possible to detect small boats on open sea up to wind forces 3 to 4 in the Beaufort wind force scale. Figure 64 illustrates the Beaufort wind force scale. However, the relatively low number of maritime surveillance campaigns carried out thus far does not allow establishing the precise sea state and wind force conditions under which small boats can be detected in spaceborne SAR imagery. In order to establish with more precision under which sea state and wind speed conditions it is possible to detect Small Boats in spaceborne SAR imagery, additional maritime surveillance experiments under different sea states and wind speeds, as well as further research are needed.



Force 0
Sea like a mirror

Force 1
Ripples with the appearance of scales are formed, but without foam crests.

Force 2
Small wavelets, still short, but more pronounced. Crests have a glassy appearance and do not break.

Force 3
Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.

Force 4
Small waves, becoming larger; fairly frequent white horses.

Force 5
Moderate waves, taking a more pronounced long form; many white horses are formed. Chance of some spray.

Figure 64 – Beaufort wind force scale: force 0 to 5 (specifications and equivalent speeds for use at sea). Pictures provided by N.O.A.A.

Table 24 shows the Pierson-Moskowitz Sea Spectrum vs Beaufort Force.

Table 24 – Pierson - Moskowitz Sea Spectrum vs Beaufort Force.

Force	Sea State	Significant Wave (Ft)	Significant Range of Periods (Sec)	Average Period (Sec)	Average Length of Waves (FT)
1	0	<.5	.5 - 1	1	2
2	1	0.5	1 - 2.5	1.5	9.5
3	2	2	1.5 - 5	3	26
4	3	3.5	2 - 6.5	4	50
5	4	6	2.5 - 8.5	5	80
6	5	8	3 - 10	6-7	130
7	6	18	4 - 13	8-9	220
8	7	32	5.5 - 17	10-12	400
9	8	52	7.5 - 23	13-15	650
10					
11	9	60-100	9 - 28.5	16-19	800-1200
12					

Other important factors affecting the detection of Small Boats in spaceborne SAR imagery are the incidence angle and the SAR image polarisation. For TerraSAR-X the full performance incidence angle range is from about 20° up to 55°. Incidence angles from 15° to 60° are available but without full performance. Concerning the polarisation of the images, HH and HV are the most suitable for targets on sea. For steep incidence angles HH seems to deliver better results. HV seems to be more suitable for low incidence angles.

Further small boat detection campaigns are needed to evaluate the feasibility of detection of small boats using spaceborne SAR imagery. Future campaigns should include different scenarios (e.g. open sea, inland waters, beach, etc.), types of boats (e.g. size, shape, material, etc.) and sea state and wind force conditions. The use of different incidence angles and polarisations should also be tested. The ground truth data collection should also be improved.

6.2 – Characterisation of SAR Small Boat Signatures

The characterisation of SAR small boat signatures is a challenging task. Any attempt to characterize SAR signatures of small boats requires the analysis of a large number of Small Boat SAR signatures acquired under different conditions and scenarios. Additional small boat detection experiments are required to generate a large amount of data to be analysed.

6.3 – Limitations of current State-of-the-Art SAR Satellite technology

The main limitations of current State-of-the-Art spaceborne SAR imagery for maritime surveillance, in particular aimed at small boat detection, are:

1. - SAR satellites repeat cycles do not allow the coverage of the same area at the required time intervals. Constellations of SAR satellites could be a solution.

2. - The conflict between resolution and image swath. High resolution is required to detect small boats. However, the high resolution images have small swaths. Maritime surveillance with high resolution images would require a large number of images to cover wide maritime areas, which is very expensive and for the time being technically not feasible. Intelligence data can play an important role by indicating an approximate position of suspicious non cooperative targets, therefore reducing the surveillance area, which can then be imaged using high resolution images.

3.- Spaceborne high resolution SAR imagery acquisition times are long enough to allow significant motion of the target during the acquisition time degrading the quality of the image. Further research efforts are needed to develop new sensors and platforms. As far as sensors are concerned, shorter integration times are needed to prevent the blurring effect caused by the motion of the targets. Regarding the platforms, more platforms are needed to allow lower repeat cycles and improved coverage.

7. – Plans for Future Work

The controlled experiments carried out in Portoroz-Slovenia comprised the deployment of small boats on open sea near Piran. The open sea trials were very successful since all boats deployed during the experiment were detected in 6 out of 7 spaceborne SAR images. The several small boat detection campaigns conducted by the EC-JRC thus far seem to suggest that the probability of detection of small boats in spaceborne SAR images strongly depends on factors, such as the sea state, the wind speed, the type of boat (shape and materials), the wave parameters and, eventually other parameters. The results are no enough to draw final conclusions about the feasibility of using spaceborne SAR imagery for small boat detection. The estimation of the probability of detection of small boats in spaceborne SAR images requires a large number of experiments under different circumstances (e.g. sea state, wind speed, characteristics of the targets, image type and mode, etc.).

Future plans include additional small boat detection experiments taking into account all the factors that have been identified as playing an important role in the detection of Small Boats in spaceborne SAR images, namely scenarios, sea state, wind speed, type of Small Boat (e.g. size, shape, materials, etc.), incidence angle, polarisation and multilook imagery Synthetic Aperture Radar.

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Abstract

The European maritime area is one of Europe's most important assets with regard to resources, security and ultimately prosperity of the Member States. A significant part of Europe's economy relies directly or indirectly on it. It is not just the shipping or fisheries industries and their related activities. It is also shipbuilding and ports, marine equipment and offshore energy, maritime and coastal tourism, aquaculture, submarine telecommunications, blue biotech and the protection of the marine environment. The European maritime area faces several risks and threats posed by unlawful activities, such as drugs trafficking, smuggling, illegal immigration, organised crime and terrorism. Piracy in international waters also constitutes a threat to Europe since it can disrupt the maritime transport chain. These risks and threats can endanger human lives, marine resources and the environment, as well as significantly disrupt the transport chain and global and local security. It is anticipated that these risks and threats will endure in the mid and long run. In order to keep Europe as a world leader in the global maritime economy, an effective integrated/interoperable, sustainable maritime surveillance system and situational awareness are needed.

A significant number of unlawful maritime activities, such as illegal immigration, drugs trafficking, smuggling, piracy and terrorism involve mainly small boats, because small boats are faster and more difficult to detect using conventional means. Hence, it is very important to find out the feasibility of using SAR Satellite images for small boat detection. Since 2008 the EC-JRC has carried out a number of SAR Small Boat detection experiments to assess the feasibility of using Spaceborne SAR for Small Boat detection. This report presents the results and conclusions of the Spaceborne SAR Small Boat detection campaign carried out by the EC-JRC on open sea in Portoroz – Slovenia in May and June 2010.

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